AD-A078 219 ARMY MILITARY PERSONNEL CENTER ALEXANDRIA VA F/G 7/2
MIX DESIGN AND RESILIENT MODULUS EVALUATION OF SULPHUR-EXTENDED--ETC(U)
NOV 79 P D SHARKEY

UNCLASSIFIED NL

1 OF 2
ADA
078219

LEVEL II

(2)

AD A078219

Mix Design and Resilient Modulus Evaluation of Sulphur-Extended Asphalt Pavements

CPT. Paul D. Sharkey
HQDA, MILPERCEN (DAPC-OPP-E)
200 Stovall Street
Alexandria, VA 22332

Final Report, 5 November, 1979

Approved for public release; distribution unlimited.

A thesis submitted to University of Washington, Seattle, Washington, in partial fulfillment of the requirements for the degree of Master of Science.

9 Final rept.,

6 Mix Design and Resilient Modulus Evaluation
of Sulphur-Extended Asphalt Pavements.

by

10 Paul Douglas Sharkey

A thesis submitted in partial fulfillment
of the requirements for the degree of

Master of Science

12 136

University of Washington

1979

11 5 Nov 79

Approved by Ronald L. Terrel
(Chairperson of Supervisory Committee

Program Authorized
to Offer Degree Civil Engineering

Date November 5, 1979

391 191 gm

In presenting this thesis in partial fulfillment of the requirements for a Master's Degree at the University of Washington, I agree that the Library shall make its copies freely available for inspection. I further agree that extensive copying of this thesis is allowable only for scholarly purposes. It is understood, however, that any copying or publication of this thesis for commercial purposes, or for financial gain, shall not be allowed without my written permission.

Signature Paul D Sharkey

Date 5 NOVEMBER 1979

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGMENTS

A project of this magnitude could not have been completed without the encouragement and assistance of many individuals. I wish to express my sincere gratitude to my Committee Chairman, Dr. Ronald L. Terrel and to my Committee Members Professor Albert L. Hoag and Dr. Joe P. Mahoney for their constant encouragement, guidance and support.

The financial assistance provided by the Federal Highway Administration (FHWA), Sulphur Development Institute of Canada (SUDIC), Washington Asphalt Pavers Association (WAPA) and the Washington State Department of Transportation (WSDOT) is appreciated.

I am very grateful to Mr. Robert L. Garman for his assistance and friendship during this project. The laboratory assistance of Dr. Sveng Rimsritong and Mr. Manoochehr Moattar is appreciated. Sincere thanks are extended to Barbara Blackman for typing the draft and final copies of this thesis.

A very special thanks is extended to my parents for giving me their guidance and understanding during all my educational experiences.

Finally, to my wife, Doris, and children Holli, Bryan and Heidi, I express my sincere appreciation and love for their faith, love and understanding during this study.

CHAPTER I

INTRODUCTION

1.1 Background

As early as 3200 B.C., asphalt was used as a waterproofing material by the Sumerians in the Euphrates Valley. The Babylonians used it as a mortar in masonry and for pavements. With the drilling of the first oil wells around 1865 and the discovery that certain crude oils yielded a material resembling native asphalt, an almost unlimited new source of asphalt became available for technical exploitation. With the development and growth of automobile and airplane transportation, asphalt paving for roads, highways, parking lots, airfields, etc., has become one of the major types of construction in the United States (1).

The primary mode of transportation in most countries is the motor vehicle. It is the considered opinion of transportation experts that the motor vehicle will remain the foremost means of transportation far into the future. Therefore, the pavements on which these vehicles travel are essential to the way of life in most countries. Over 93 per cent of all pavements in the United States are surfaced with asphaltic concrete. Other countries have similarly high percentages of asphalt pavements (2).

With the advent of the fuel shortage, it has become more lucrative for petroleum refiners to use asphalt in the blending of heavy fuel oil than to market it as cement. This has resulted in a

substantial increase in the price of asphalt cement and hence, the price of asphaltic concrete (3). The high price and questionable availability of asphalt cement in the future has led to the investigation of alternate binders.

A suitable substitute binder must be effective and economically available in large quantities to meet the demands of the paving industry. Based on current industrial trends, sociological demands and reasonably firm data gathered by the sulphur industry, elemental sulphur will, in the very near future, meet the dual requirements of economic availability (4). In many areas of the world, large amounts of sulphur are now being recovered from natural gas and petroleum. Existing world stockpiles are estimated to be 26 million metric tons due primarily to pollution abatement processes (5). Over the next five to ten years recovered sulphur production is expected to increase sharply, with the Middle East in particular becoming a major supplier. By 1982, Saudi Arabia alone will be producing almost one and one-half million long tons of sulphur per year (6).

There have been two methods in which sulphur has been used in asphalt concrete. The first method incorporates elemental sulphur as a partial replacement and/or extender of asphalt cement (3). These mixtures are known as sulphur-extended asphalt (SEA) mixtures (7). Secondly, sulphur may be used as a structuring agent in mixtures which contain poorly graded sands. These mixtures are known as sand-asphalt-sulphur (SAS) (8).

A number of organizations have played a significant role in sulphur-asphalt research. These organizations include the Federal Highway Administration (FHWA), Gulf Oil Limited of Canada, Shell Canada Limited, Societe Nationale Elf Aquitaine (SNEA), the Sulphur Development Institute of Canada (SUDIC), the Sulphur Institute, the Texas Transportation Institute (TTI) and the United States Bureau of Mines.

These organizations have conducted numerous laboratory-analytical studies to investigate the effect of combining sulphur, asphalt and various aggregates in asphalt concrete mixtures. These studies have indicated that sulphur-asphalt mixtures perform as well or better than conventional asphalt concrete mixtures (3, 9, 10, 11, 12, 13, 14, 15).

The University of Washington is performing a study sponsored by the Washington State Department of Transportation to plan, construct, monitor and evaluate a sulphur-extended asphalt project. The project is intended to bridge the gap between the laboratory-analytical studies and the full-scale experimental highway projects. This project comprises building full-depth pavement structures for repetitive wheel load testing at the Washington State University (WSU) test track as well as participation in the construction and evaluation of a full-scale experimental highway project near WSU.

The equipment at the test track consists of a 15-ton structural steel frame (Figures 1.1 - 1.2) and water tank revolving over an 83-ft diameter ring. This applies a 10,600-lb load to each of three sets

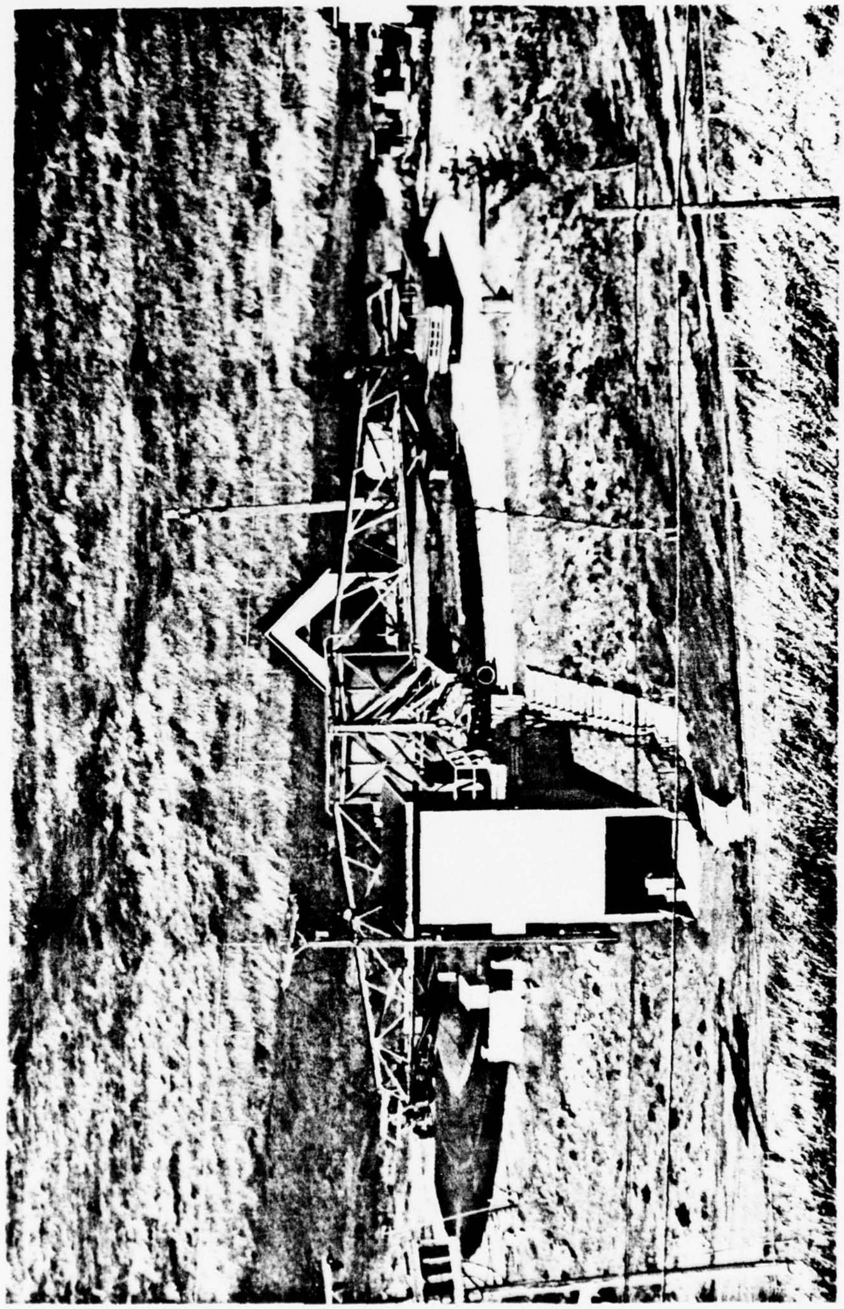


Figure 1.1 TEST TRACK - WASHINGTON STATE UNIVERSITY

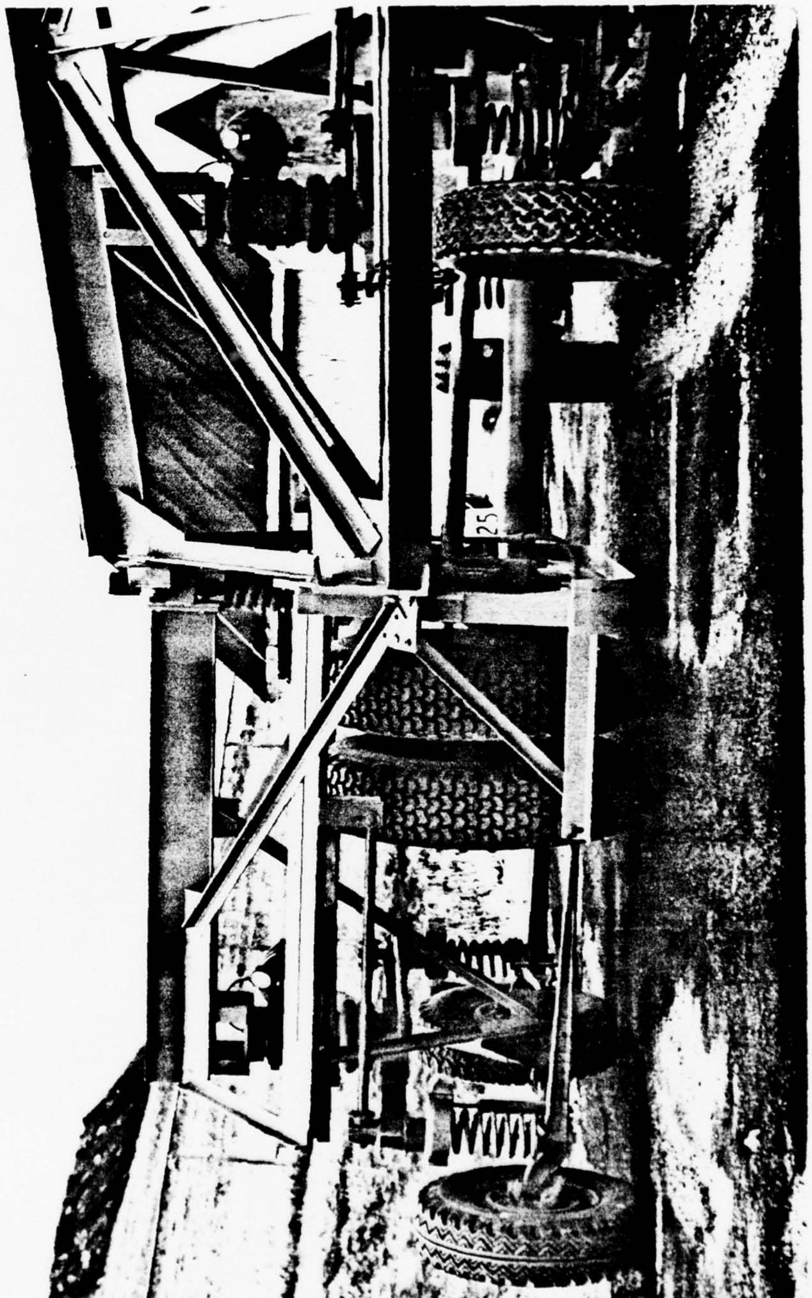


Figure 1.2 WHEEL AND TIRE ARRANGEMENT

of dual wheels. Water can be added to the tank to bring the total load on each set of dual wheels to over 20,000 lbs. To keep the wheels from continually moving in the same track, the center of rotation of the structure is designed so that various wheel path widths and load distributions can be applied to the pavement structure. The loading frame is guided by a 6.5-in diameter vertical steel center shaft. This shaft rotates in a self-aligning bearing mounted in a power-driven revolving frame. Each set of dual wheels is 41.5-ft from the axis of rotation (16).

The experimental pavement ring was built of sections representing different sulphur-asphalt binder ratios and layer thicknesses. All sections were covered by a *minimum* of one inch of 70/30 SEA pavement. Figure 1.3 shows the schematic profile and Figure 1.4 the corresponding plan view of the test track layout (16).

The full scale highway project is located near Pullman on SR-270. The project involves overlaying 4223-lf of conventional pavement with .15-ft of various sulphur-asphalt binder ratio pavements. Figure 1.5 contains a plan view of the highway layout (16).

This unique opportunity has allowed for the concurrent construction of both the test track and the experimental highway project. The same materials and central batch plant were used for both jobs. Thus the WSU test track construction and resulting evaluation is being used as an accelerated test of similar pavement materials which were also in the experimental highway project (16).

There are a number of unique advantages involved in using the test track concept. One is that a limited number of variables are

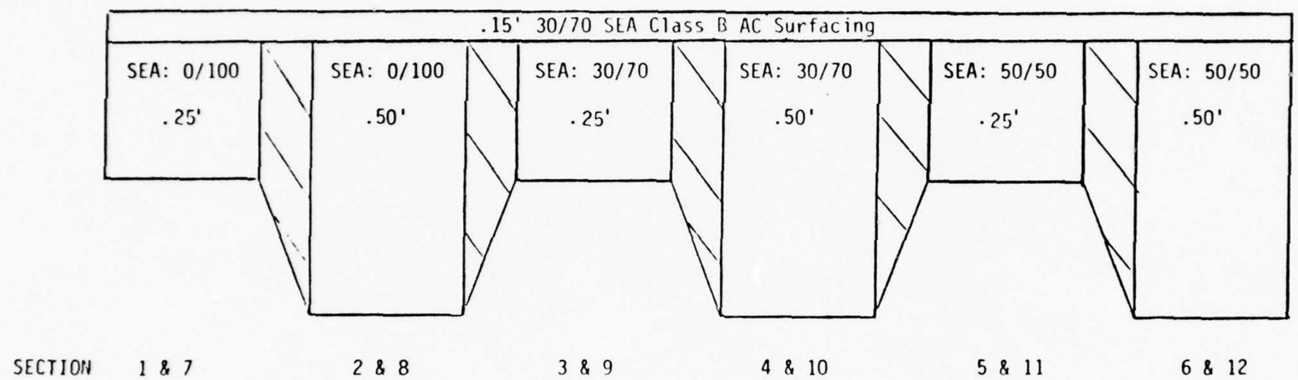


Figure 1.3 SCHEMATIC PROFILE OF TEST TRACK

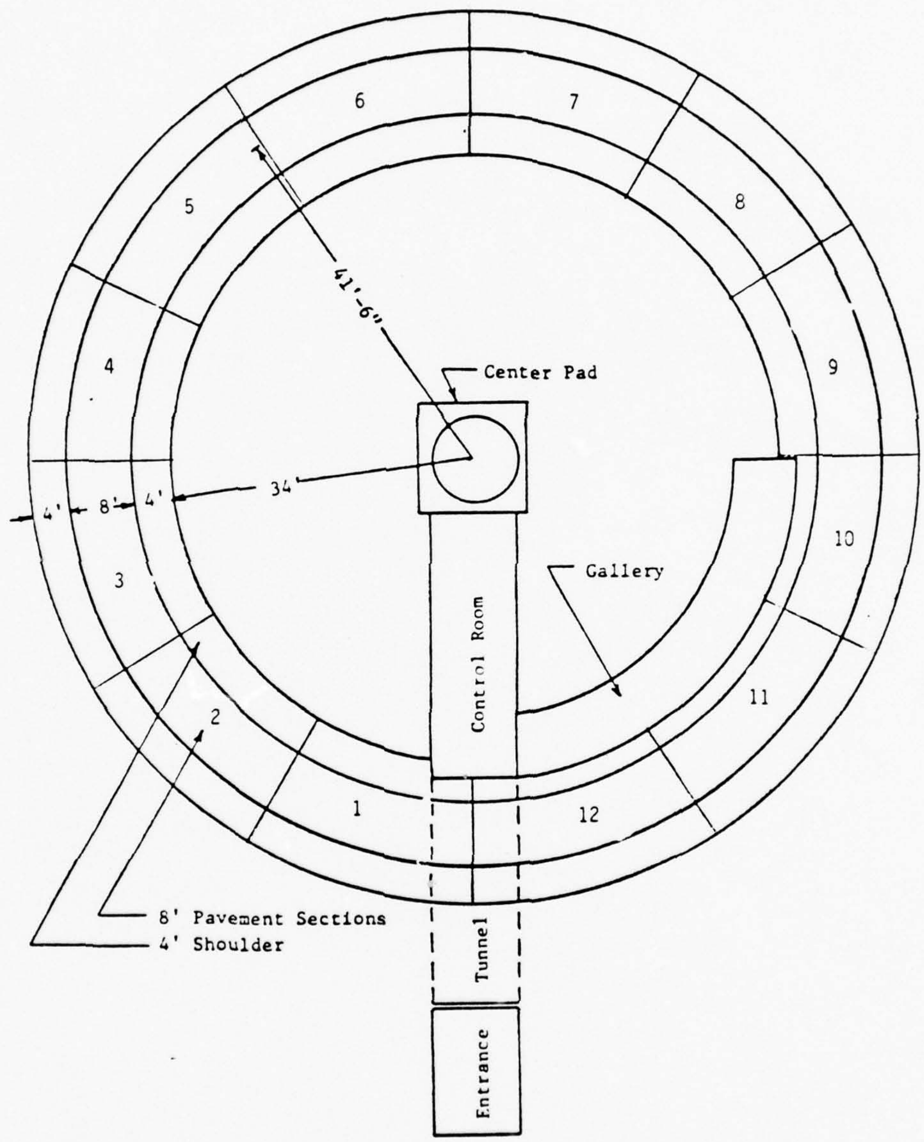


Figure 1.4 PLAN VIEW OF TEST TRACK

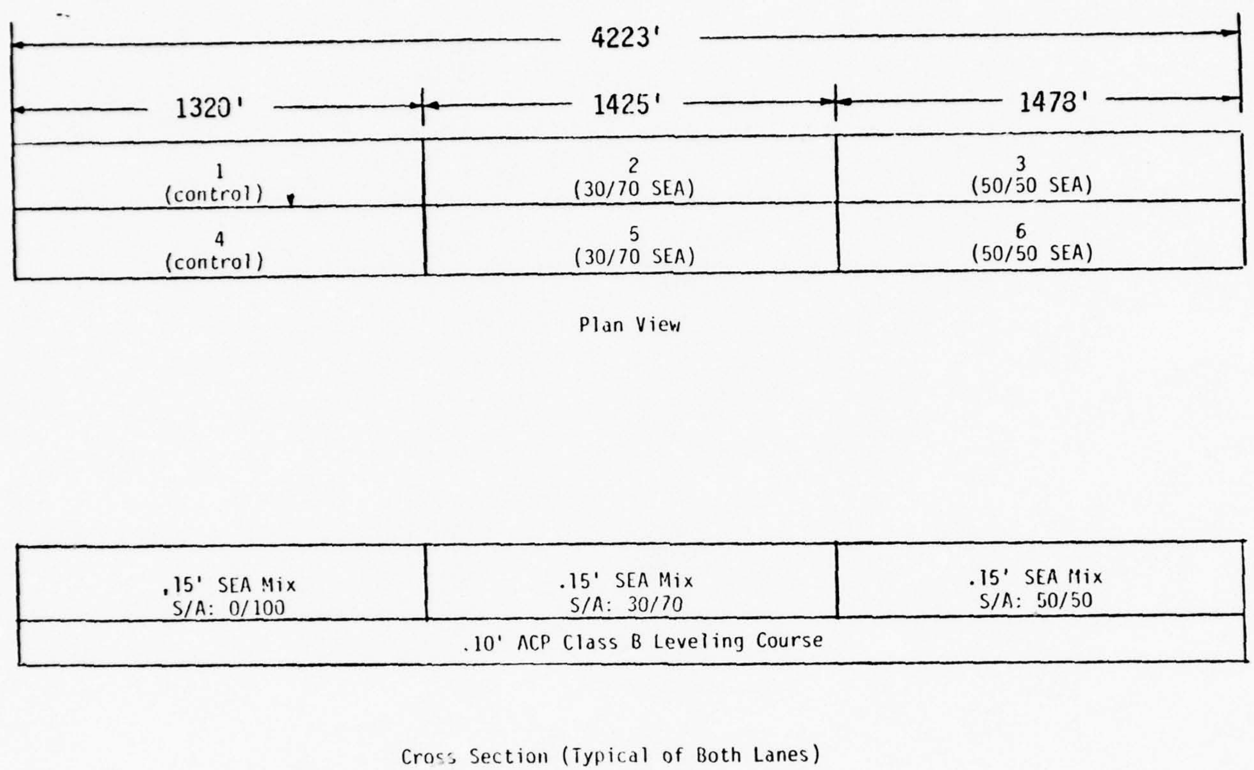


Figure 1.5 PLAN VIEW OF HIGHWAY LAYOUT

carefully monitored under controlled conditions. The use of a test track thus eliminates many of the uncertainties and variabilities encountered in constructing and evaluating experimental highway projects. It is also a more realistic assessment of the performance of the composite pavement structure than obtained through laboratory studies. Additionally, a conventional asphalt batching plant and laydown machinery are used to produce and place the various mixtures and thicknesses to be investigated. It is important to simulate actual highway construction procedures to the extent possible (16).

1.2 Objective

The purpose of this thesis is threefold:

1. Design, by the Marshall mix design method, an optimum asphalt/SEA binder content for the proposed project.
2. Design, by the Hveem mix design method, an optimum asphalt/SEA binder content for the proposed project.
3. Investigate the resilient modulus values of the various SEA binder ratios at varying temperatures and determine if this test procedure can be used in determining optimum binder contents for the mixtures studied.

1.3 Scope

To accomplish the above objectives, several tasks are required:

1. Prepare a test sequence, test the materials to be used and prepare the test samples.
2. Test the samples according to the Marshall and Hveem mix design test procedures.
3. Test the samples for resilient modulus values.

Each of the above tasks are the subject of the following chapters, which describe the investigation in detail.

CHAPTER II

MATERIALS TESTING, SAMPLE PREPARATION AND TESTING

2.1 Materials Testing

Prior to the preparation of the asphalt test samples, preliminary testing was conducted on the materials to be used. These materials were obtained from the contractor to ensure that the field trial would correspond directly to the laboratory analysis. The aggregate, a basalt obtained from a quarry in Pullman, Washington, was tested for specific gravity and absorption according to ASTM C 127 (17). The results were 2.74 and 2.29 for the specific gravity and absorption respectively. The asphalt cement, an AR-4000 obtained from the United Paving Asphalt Plant in Pullman, Washington and produced by Husky Oil, was tested in accordance with ASTM D 70 (18) for specific gravity, which was found to be 1.024. The sulphur was an 80 mesh ground sulphur from the Montana Sulphur and Chemical Company, Billings, Montana. The sulphur was not tested due to the apparent purity.

2.2 Sample Preparation

Forty-five Marshall mix design samples were then prepared in three sets of 15 samples each. Set A had an asphalt/sulphur ratio of 100/0, Set B had an asphalt/sulphur ratio of 50/50 and Set C had an asphalt/sulphur ratio of 70/30.

A gradation similar to that shown in Table 2.1 and Figure 2.1 was used for all the laboratory specimens prepared in this study. The coarse side of the Class B allowable band was used since previous

Table 2.1. AGGREGATE GRADATION
WSDOT CLASS "B"

SIEVE SIZE	% RETAIND	% PASSING CUMULATIVE	SPEC. LIMITS
5/8	0	100	100
1/2	7	93	90-100
3/8	16	77	75-90
1/4	19	58	55-75
No. 10	24	34	32-48
No. 40	18	16	11-24
No. 80	6	10	6-15
No. 200	5	5	3-7
No. -200	5	0	0

studies had indicated unusually low void contents for mixtures with a gradation in the middle of the band (19, 20). The gradation was accomplished by sieving the aggregate onto separate sieves and then mixing in the proportion shown in Table 2.1. The gradation used in this study met the specification of the Washington State Department of Transportation (WSDOT) for Class B asphalt concrete (21).

Figure 2.2 illustrates the Marshall sample preparation sequence. The samples were prepared in accordance with ASTM D 1559 (22) with modifications used by Pronk (23). One modification was the blending of the asphalt and sulphur. They were blended in a Scovall, Hamilton Beach Division, Model No. 936-1 drink mixer at the medium speed for three minutes. Another modification is the addition of an additive to the blended binder. Pronk (24) has demonstrated that an additive, Dow Corning 200, facilitates the dispersion of the sulphur in the asphalt and after emulsification, improves the stability of the emulsion. The final modification was reducing the temperature of the mixture before compaction.

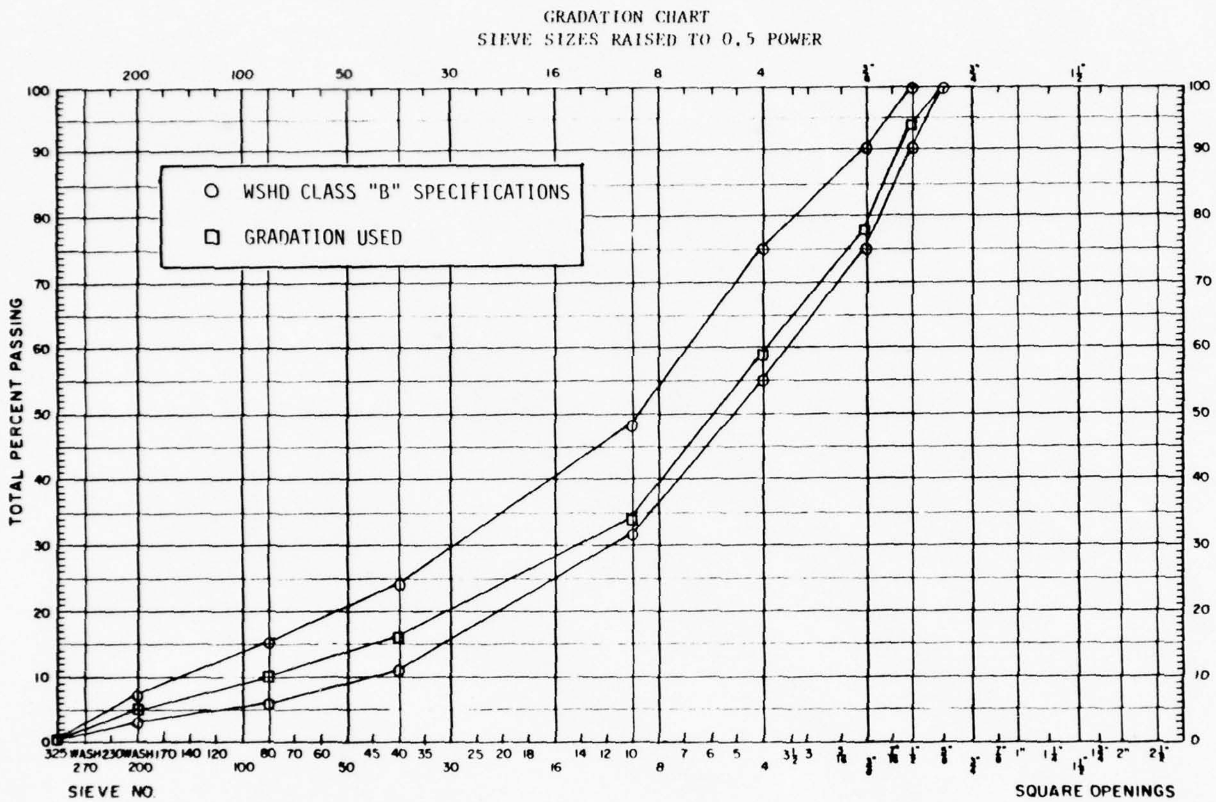


Figure 2.1 AGGREGATE GRADATION, WSDOT CLASS "B"

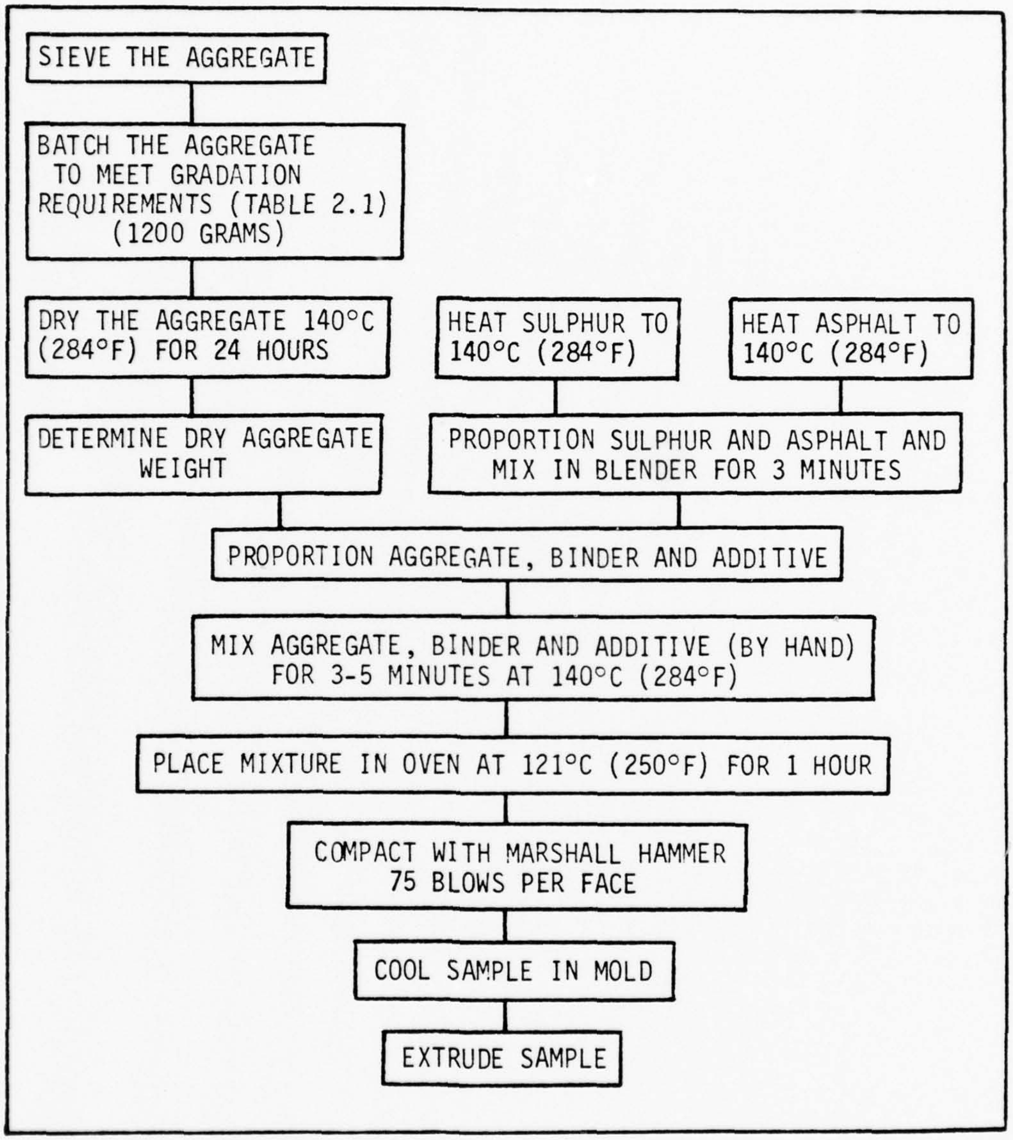


Figure 2.2 MARSHALL SAMPLE PREPARATION

The sulphur in a sulphur/asphalt emulsion exists as three distinct fractions: a portion chemically reacts with the asphalt, some is in solution in the asphalt and the remainder forms a separate dispersed phase in the asphalt (25, 26, 27). Temperature control is one of the most important aspects of paving with sulphur-asphalt. The working range of molten sulphur and paving grade asphalt are quite similar. This is generally considered to be between 124° and 149°C (225° and 300°F). Figure 2.3 shows a temperature viscosity curve for sulphur and from this it can be seen that molten sulphur becomes very viscous at higher temperatures. Sulphur is essentially unworkable at temperatures above 157°C (315°F) (7). Additionally, at temperatures in excess of 140°C (284°F) detectable amounts of hydrogen sulphide are evolved from the mixture, indicating that some dehydrogenation of the chemically reactive napthene-aromatic fraction of the asphalt is occurring with a resultant increase in the asphaltene fraction. However, the predominant reaction at these temperatures is one of insertion of sulphur to form aromatic polysulphides (23). For these reasons, it is essential that the temperature of the sulphur, S/A binder and SEA mixture be carefully monitored throughout the entire production process.

The Hveem mix design samples were prepared in the same manner as the Marshall mix design samples with the exception of the change in compaction methods. Figure 2.4 shows the Hveem sample preparation sequence. Sets D, E and F had asphalt/sulphur ratios of 100/0, 50/50 and 70/30 respectively.

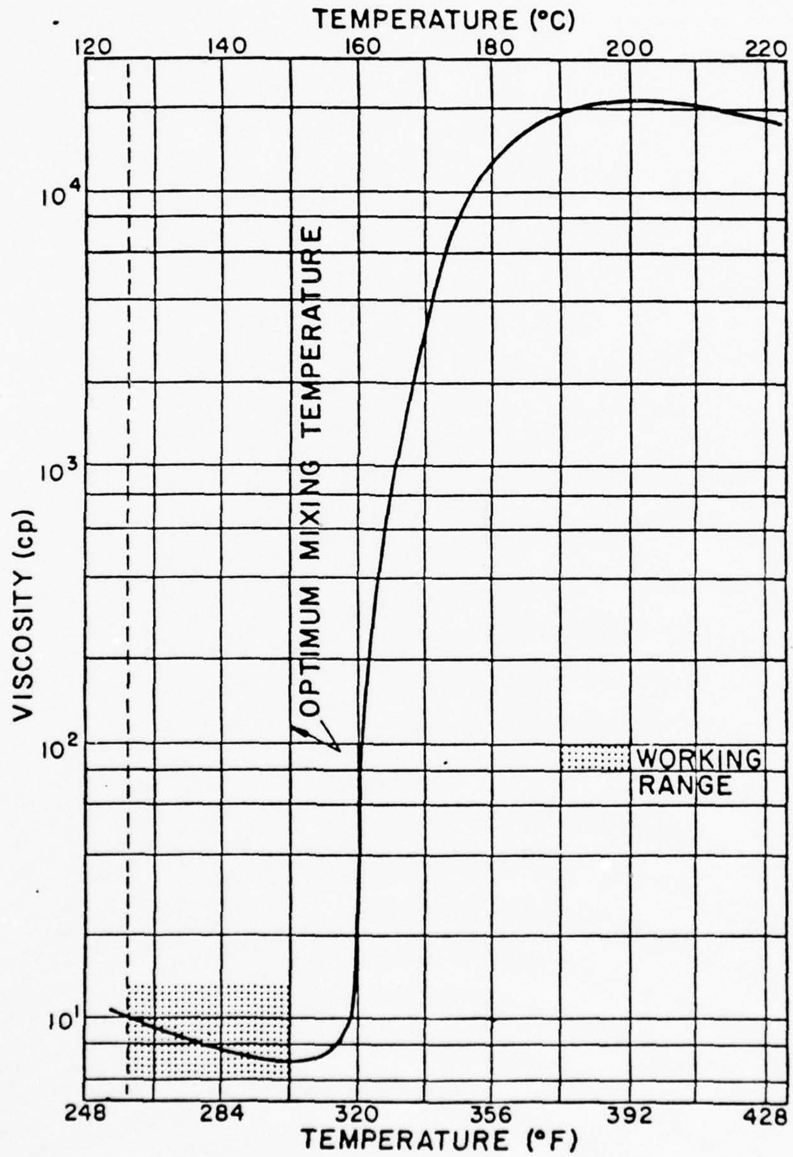


Figure 2.3 TEMPERATURE-VISCOSITY CURVE FOR LIQUID SULPHUR

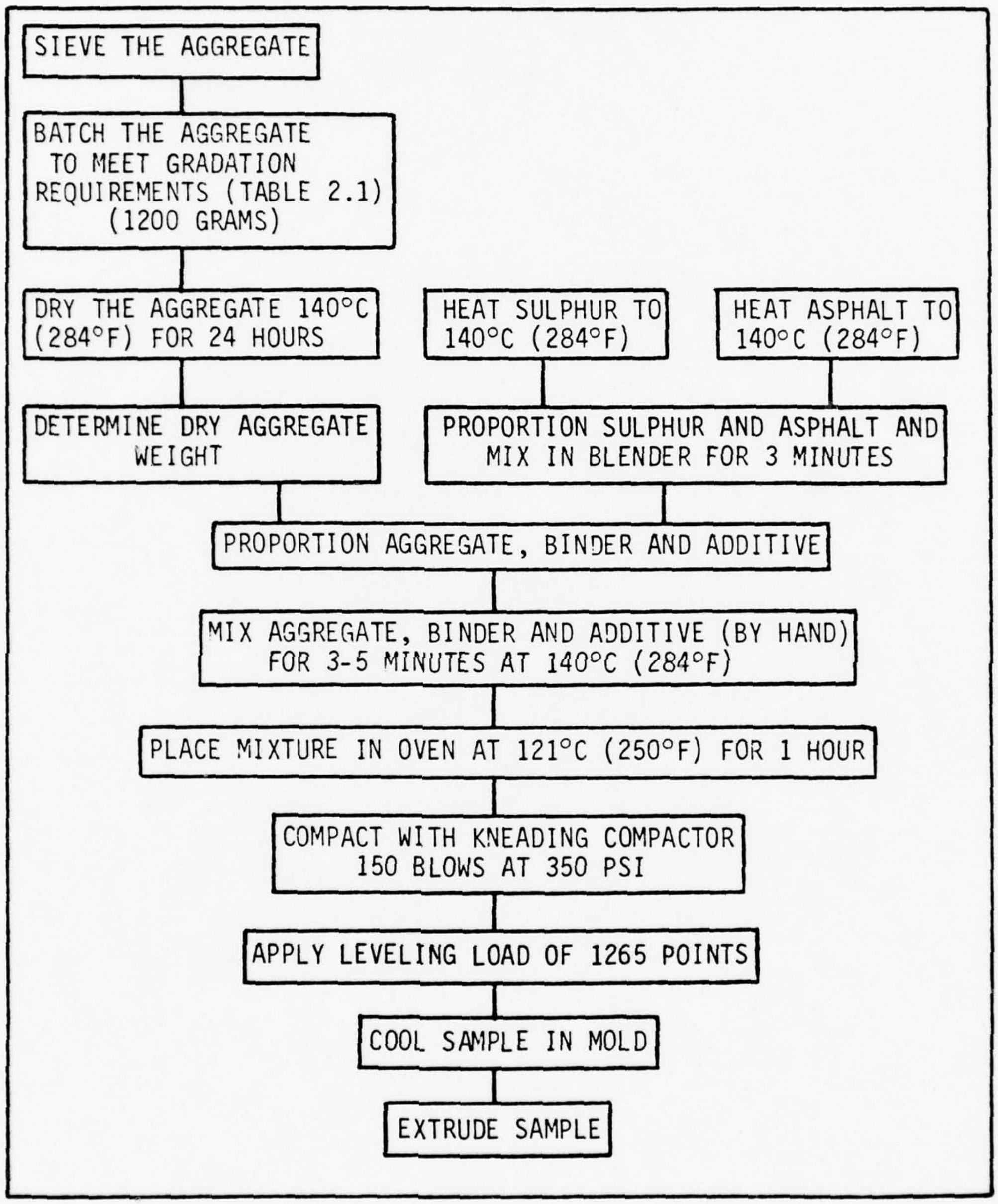


FIGURE 2.4 HVEEM SAMPLE PREPARATION

2.3 Test Sequence

After the samples were prepared, a series of tests were performed on each sample. Figures 2.5 and 2.6 show the testing sequence for the Marshall and Hveem samples respectively. A brief description of each test follows.

2.3.1 Resilient Modulus

Each sample was tested for resilient modulus in accordance with a proposed draft of an ASTM standard method (28). This draft is entitled "Indirect Tensile Test Method for Resilient Modulus of Bituminous Mixtures" and is included as Appendix A. In this test, the samples are subjected to a repetitive (pulsating) load (100 lb) of 0.1 seconds duration and 1.9 seconds dwell time applied vertically. A typical loading pattern is shown in Figure 2.7. The dynamic load results in the dynamic deformations across the horizontal plane. These deformations are recorded by transducers mounted on each side of the horizontal axis of the sample. The resilient modulus apparatus is shown in Figure 2.8.

The resilient modulus value was calculated using the following formula:

$$M_R = \frac{P(\mu + 0.2734)}{t\Delta h}$$

where

P = vertical pressure (100 lb.)
μ = Poisson's ratio
t = thickness
Δh = deformation calculated from amplitude of graph from strip chart recorder

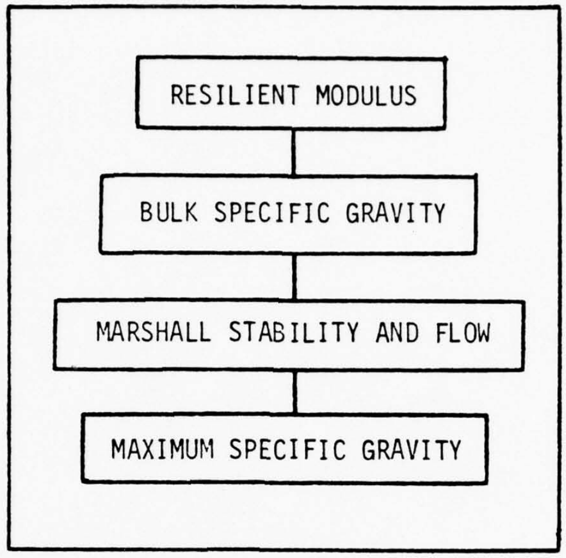


Figure 2.5. MARSHALL SAMPLE TESTING SEQUENCE

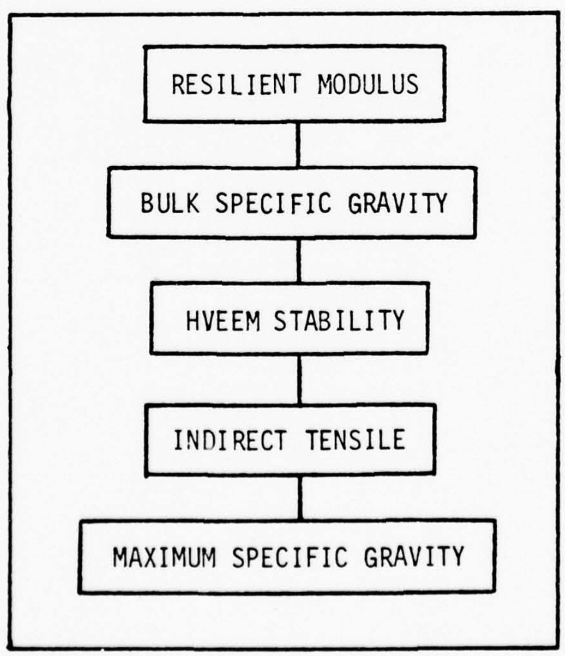


Figure 2.6. HVEEM SAMPLE TESTING SEQUENCE

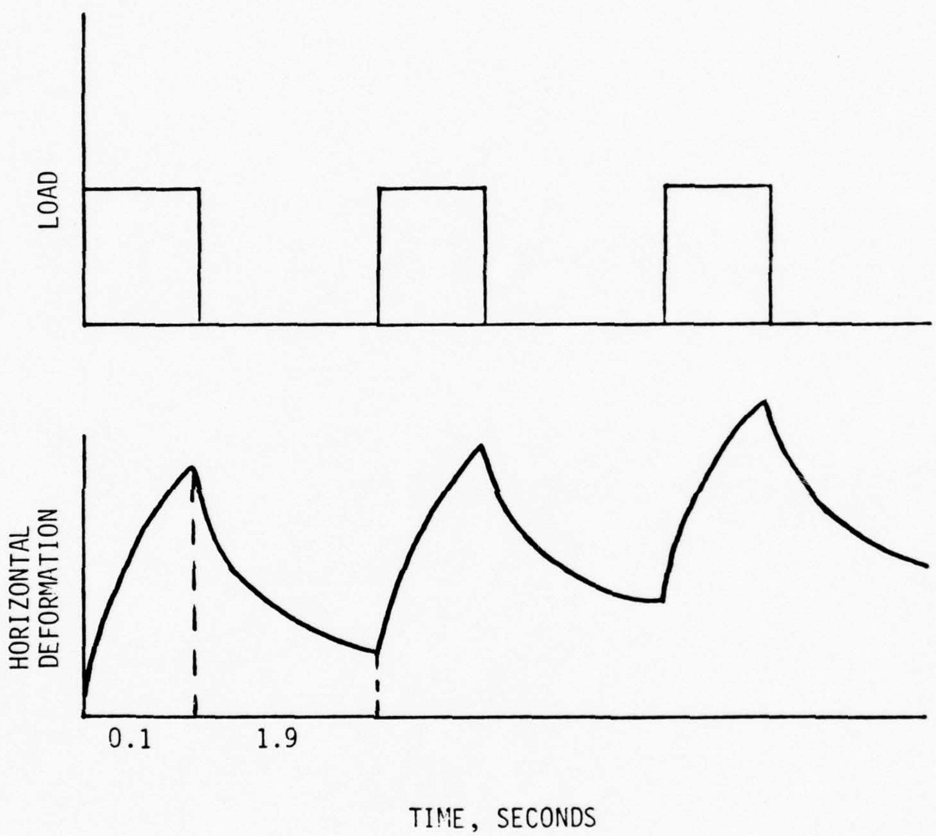


Figure 2.7. RESILIENT MODULUS LOADING PATTERN

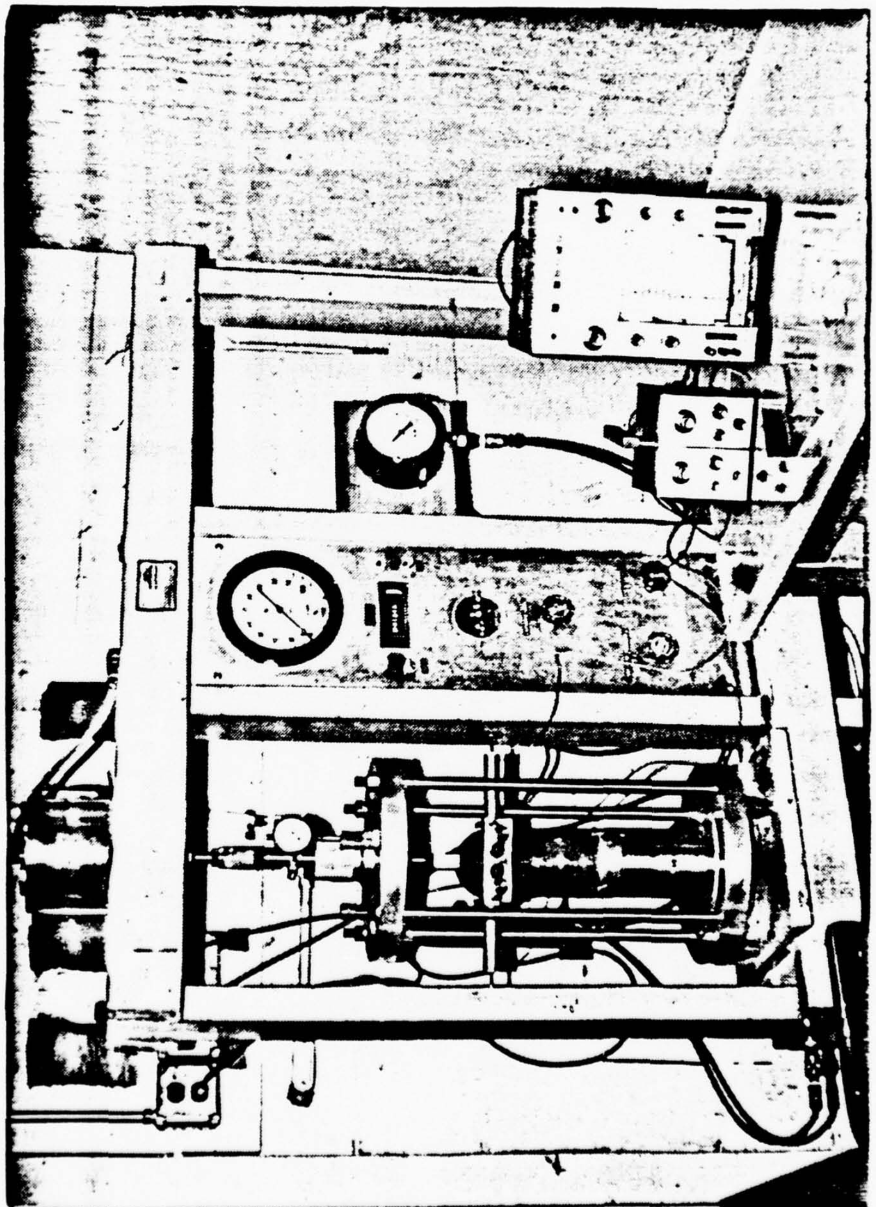


Figure 2.8 RESILIENT MODULUS APPARATUS

Each sample was tested for resilient modulus for seven consecutive days at 25°C (77°F). In addition, the samples were tested at 5°C (41°F) and 40°C (104°F) on Day 7. All samples at 5°C (41°F) and 40°C (104°F) were tested within three minutes of removal from cooling or heating unit to minimize the change in temperature. Results of this test are discussed in Chapter 4.

2.3.2 Bulk Specific Gravity

Each sample was tested for bulk specific gravity in accordance with WSDOT Test Method 704 (29). In this test, the weight of the sample is taken in air and water. The bulk specific gravity is calculated using the following formula:

$$\text{bulk specific gravity} = \frac{A}{A - C}$$

where:

A = weight of sample in air

C = weight of sample in water

2.3.3 Marshall Stability and Flow

Each sample was tested for Marshall stability and flow in accordance with ASTM Test Designation D 1559 (22). In this test, each sample is heated (in water) to 60°C (140°F) for 30 - 40 minutes prior to testing. The sample is then placed in a loading head and a load is applied at a rate of 2" per minute (Figure 2.9). The load required to cause failure is the Marshall stability. The Marshall flow is the deformation of the sample from the start of the test to

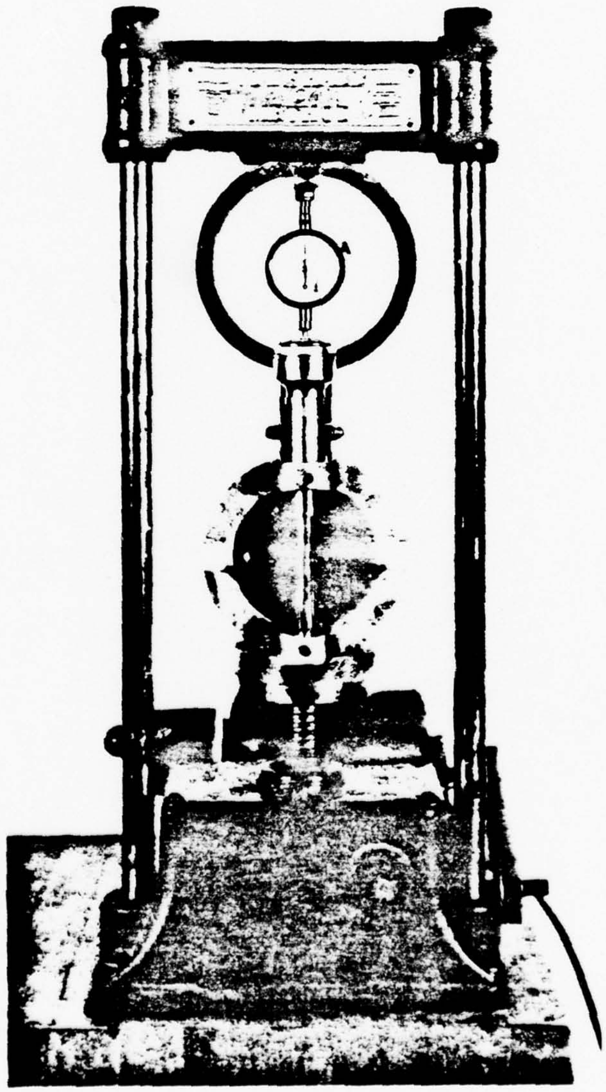


Figure 2.9 MARSHALL TESTING DEVICE

the failure of the sample. Each sample was tested within 30 seconds of removal from the water to minimize the change in temperature. Results of this test are found in Chapter 3.

2.3.4 Hveem Stability

Each sample was tested for Hveem stability in accordance with WSDOT Test Method 703 (30). In this test, samples are heated to 60°C (140°F) for two hours prior to testing and then placed in the Hveem stabilometer. A gradually increasing vertical load is applied at a rate of 0.05 inch per minute and the lateral pressure is read from a hydraulic gauge. Figure 2.10 illustrates a Hveem stabilometer. The Hveem stabilometer value was calculated using the following formula:

$$S = \frac{22.2}{[(P_h \times D_2)/(P_v - P_h)] + 0.22}$$

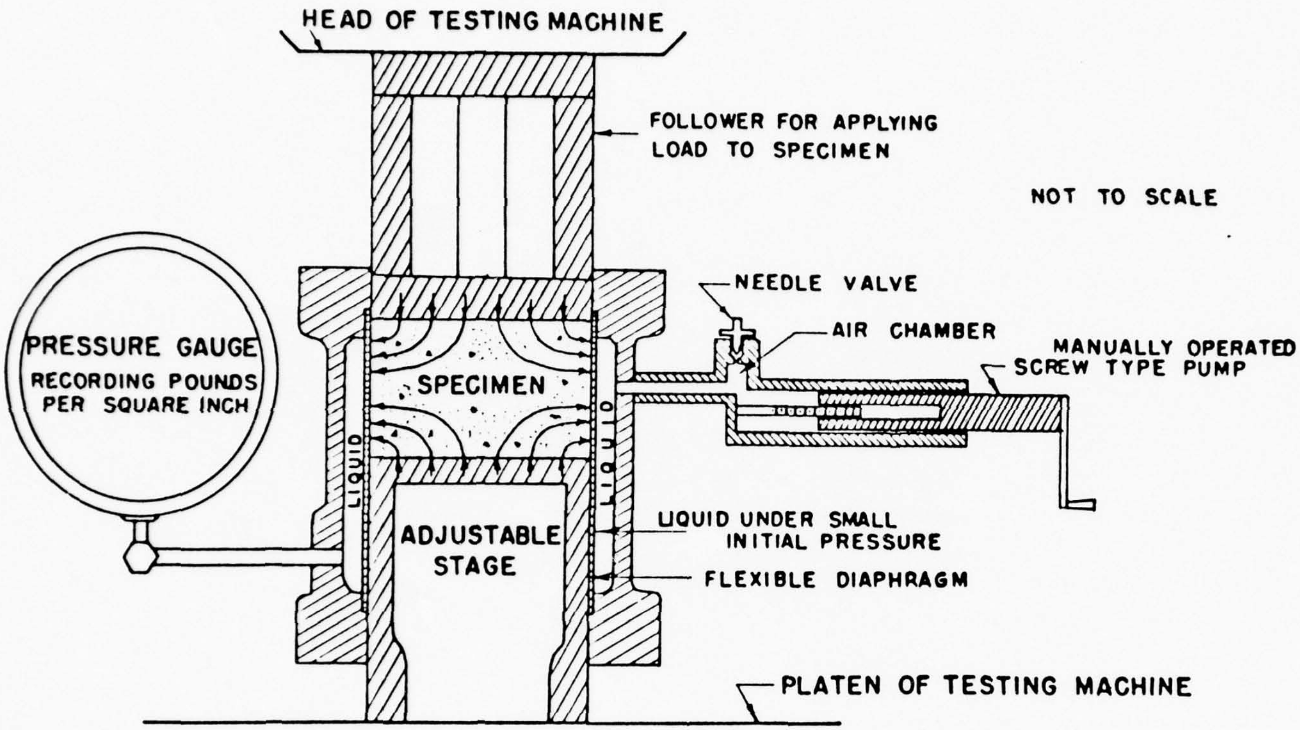
where:

S = stabilometer value
P_h = horizontal pressure, for a corresponding P_v
D_2 = displacement on specimen
P_v = vertical pressure (typically 400 psi)

Results of this test are found in Chapter 3.

2.3.5 Indirect Tensile Strength

The indirect tensile test is one type of tensile strength test used for stabilized materials. Most of the reported test results have been for concrete or mortar (31); however, the test has been conducted on cement treated gravel, lime-soil mixtures, and asphalt stabilized materials. This test involves loading a cylindrical



NOTE: SPECIMEN GIVEN LATERAL SUPPORT BY FLEXIBLE SIDE WALL WHICH TRANSMITS HORIZONTAL PRESSURE TO LIQUID MAGNITUDE OF PRESSURE MAY BE READ ON GAUGE

Figure 2.10 HVEEM STABILOMETER

specimen with a compressive load along two opposite generators. This results in a relatively uniform tensile stress acting perpendicular to and along the diametral (diameter) plane of the applied load. This results in a splitting failure generally occurring along the diametral plane (32). Figure 2.11 demonstrates this failure mode.

In this test, each sample is heated to 25°C (77°F). The sample is then placed in the indirect tensile testing device and is loaded at a rate of two inches per minute. Each sample was tested within two minutes of removal from the oven to minimize the change in temperature.

The indirect tensile strength was calculated using the following formula:

$$\text{indirect tensile strength} = \frac{2P_{max}}{\pi td}$$

where:

P_{max} = maximum total load applied

t = sample thickness

d = sample diameter (4")

Results of this test are found in Chapter 3.

2.3.6 Rice Maximum Specific Gravity

Each sample was tested for maximum specific gravity in accordance with WSDOT Test Method 705 (33). In this test, each sample is broken into small pieces not larger than 0.25-in. These pieces are put into a container, covered with water and subjected to a partial vacuum of

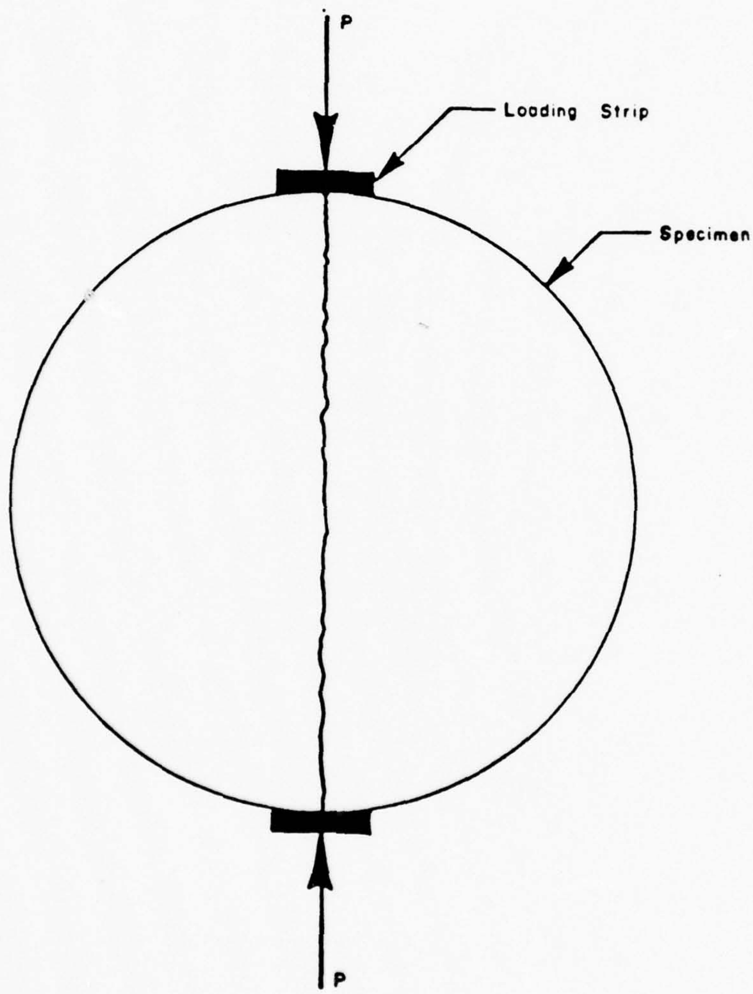


Figure 2.11 INDIRECT TENSILE SET-UP

25 mm Hg for 15 $\pm$ 2 minutes. The maximum specific gravity is calculated using the following formula:

$$\text{maximum specific gravity} = \frac{A}{A + D - E}$$

where:

A = weight of dry sample in air

D = weight of container filled with water at 25°C (77°F)

E = weight of container filled with water and sample at 25°C (77°F)

CHAPTER III

MIX DESIGN EVALUATION

3.1 Marshall Method

3.1.1 Background

The Marshall mix design method was developed by Mr. Bruce Marshall, formerly bituminous engineer for the Mississippi State Highway Department. The U.S. Army Corps of Engineers, through extensive research, has improved the Marshall method, and ultimately has developed the Marshall mix design criteria. The Marshall method is based on density/voids and resistance. The resistance is tested by means of the Marshall testing machine (Figure 2.9). The density/voids are determined by measuring the specific gravity of the mixture and, by using standard formulas, calculating the density/voids values (34).

The Marshall samples were prepared and tested in accordance with Figures 2.2 and 2.5. The five binder content percentages tested were 4.5, 5.0, 5.5, 6.0 and 6.5 by total weight of mix. For the 100/0 samples, since sulphur and asphalt do not have the same specific gravity (sulphur is approximately twice that of asphalt), an adjustment must be made to the sulphur/asphalt binders to equate them as equal volumes when compared to conventional asphalt binder.

The factors used were: 100/0 = 1.00, 50/50 = 1.3442, and 70/30 = 1.1828 (23).* The sulphur/asphalt binder content percentages then become 6.1, 6.7, 7.4, 8.1, and 8.8 for the 50/50 SEA samples and 5.3, 5.9, 6.5, 7.1, and 7.7 for the 70/30 SEA samples.

3.1.2 Results

The data obtained on the Marshall samples are presented in Tables 3.2 through 3.4 and Figures 3.1 through 3.3.

3.1.3 Discussion of Results

The results of the Marshall testing should be compared to the standard criteria shown in Table 3.1. The optimum binder content of the paving mix is determined by graphing the results and comparing them to Table 3.1. Consideration is given to three of the test data curves in making this determination. From these curves, binder contents are determined which yield the following:

(a) maximum stability

(b) maximum unit weight

(c) median of limits given in Table 3.1 for air voids

The optimum binder content of the mix is then the numerical average of the values for the binder content determined above (34).

---

*The equivalent weights of sulphur/asphalt binders will be presented in parentheses ( ) in the remainder of this report.

Table 3.1 MARSHALL DESIGN CRITERIA (34)

Traffic category	Heavy	
Number of compaction blows each end of specimen	75	
	Minimum	Maximum
Stability, lb	750	
Flow, 0.01-in	8	16
Per cent air voids		
surface course	3	5
base course	3	8
Per cent voids in mineral aggregate	14	

The results of this determination for each asphalt/sulphur ratio binder are presented below:

<u>100/0 Asphalt/Sulphur Ratio</u>

Data Type	Value	Binder Content
Stability	4061-lb	5.0
Unit weight	155.4 pcf	5.0
Air voids	4.0%	5.0
Optimum binder content		5.0

<u>50/50 Asphalt/Sulphur Ratio</u>

Data Type	Value	Binder Content
Stability	11,243-lb	4.5 (6.1)
Unit weight	156.0 pcf	5.0 (6.7)
Air voids	4.4%	6.0 (8.1)
Optimum binder content		5.2 (7.0)

Table 3.2. MARSHALL MIX DESIGN DATA
100/0 ASPHALT/SULPHUR RATIO

BINDER CONTENT (%) BY WEIGHT	SAMPLE	WEIGHT IN AIR (GRAMS)	WEIGHT IN WATER (GRAMS)	BULK SPECIFIC GRAVITY	UNIT WEIGHT	MAXIMUM SPECIFIC GRAVITY	VMA	% AIR VOIDS	STABILITY MEASURED	STABILITY ADJUSTED	FLOW
4.5	A_1	1231.0	726.0	2.437	152.3	2.514			3700	3552	19
	A_2	1225.5	723.5	2.441	152.3	2.506			3450	3312	19
	A_3	1227.5	725.0	2.444	152.3	2.575			3150	3150	19
				2.440	152.3	2.532	16.8	3.6		3338	19.0
5.0	A_4	1232.5	735.0	2.477	154.8	2.595			3400	3876	17
	A_5	1239.0	741.0	2.487	155.4	2.591			3840	4186	17
	A_6	1246.5	748.0	2.500	156.0	2.597			3780	4120	18.1
				2.488	155.4	2.594	15.5	4.0		4061	17.4
5.5	A_7	1243.0	739.5	2.468	154.1	2.564			3560	3560	19
	A_8	1233.5	731.0	2.454	153.5	2.558			3600	3600	19
	A_9	1247.0	741.0	2.464	153.5	2.542			3780	3780	24
				2.462	153.7	2.555	16.9	3.6		3647	20.7
6.0	A_{10}	1242.0	744.0	2.494	155.4	2.539			3460	3598	20
	A_{11}	1238.0	738.0	2.476	154.8	2.519			3200	3328	23
	A_{12}	1255.0	745.0	2.460	153.5	2.530			2900	2900	18
				2.476	154.6	2.529	16.9	2.1		3275	20.3
6.5	A_{13}	1251.0	751.5	2.504	156.0	2.508			3080	3203	22
	A_{14}	1248.0	750.0	2.506	156.6	2.518			3450	3450	23
	A_{15}	1254.0	752.0	2.498	156.0	2.529			3300	3168	20
				2.502	156.2	2.518	16.4	0.6		3274	21.7

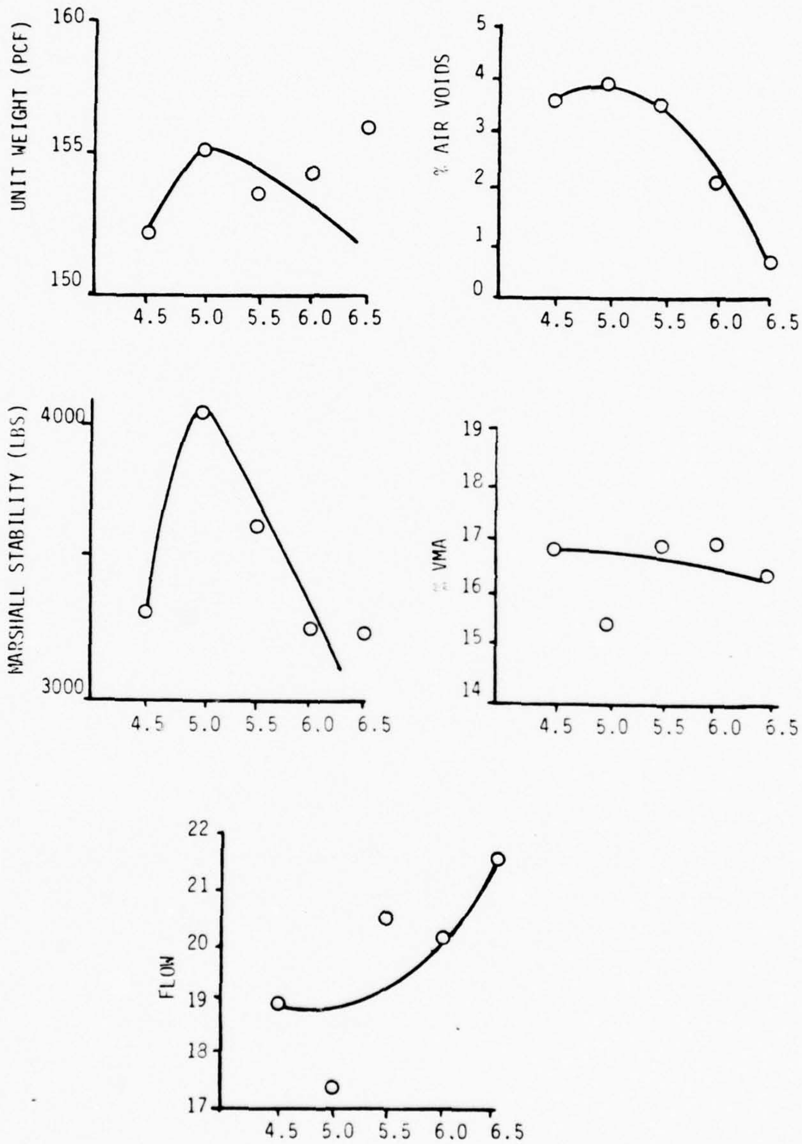


Figure 3.1. MARSHALL MIX DESIGN DATA CURVES
100/0 ASPHALT/SULPHUR RATIO

Table 3.3. MARSHALL MIX DESIGN DATA
50/50 ASPHALT/SULPHUR RATIO

BINDER CONTENT (%) BY WEIGHT	SAMPLE	WEIGHT IN AIR (GRAMS)	WEIGHT IN WATER (GRAMS)	BULK SPECIFIC GRAVITY	UNIT WEIGHT	MAXIMUM SPECIFIC GRAVITY	VMA	% AIR VOIDS	STABILITY MEASURED	STABILITY ADJUSTED	FLOW
4.5	B_1	1226.5	734.5	2.493	155.4	2.541			10,900	11,881	18.8
(6.1)	B_2	1253.0	751.0	2.496	156.0	2.667			11,040	12,034	24.0
	B_3	1242.0	744.0	2.494	155.4	2.660			8,610	9,815	23.0
				2.494	155.6	2.623	15.0	5.0		11,243	22.0
5.0	B_4	1261.0	758.0	2.507	156.6	2.644			11,260	12,273	29.0
(6.7)	B_5	1252.5	749.0	2.488	155.4	2.632			9,800	10,682	30.0
	B_6	1255.0	752.5	2.496	156.0	2.611			9,650	10,519	29.0
				2.497	156.0	2.629	15.2	4.9		11,158	29.3
5.5	B_7	1264.0	754.5	2.481	154.8	2.640			9,340	10,181	27.0
(7.4)	B_8	1263.0	758.0	2.500	156.0	2.564			8,540	9,309	25.0
	B_9	1272.0	759.5	2.482	154.8	2.604			8,720	9,505	26.5
				2.488	155.2	2.603	16.1	4.5		9,665	26.2
6.0	B_{10}	1265.0	744.5	2.430	151.6	2.551			9,150	9,516	24.0
(8.1)	B_{11}	1273.5	761.5	2.489	155.4	2.609			6,500	7,085	21.0
	B_{12}	1260.0	756.5	2.502	156.0	2.599			6,720	7,325	22.0
				2.474	154.3	2.586	17.0	4.4		7,975	22.3
6.5	B_{13}	1273.0	762.0	2.491	155.4	2.608			5,550	5,772	19.0
(8.7)	B_{14}	1258.0	740.0	2.429	151.6	2.514			6,680	6,947	21.5
	B_{15}	1281.5	749.5	2.409	149.8	2.546			6,320	6,320	21.5
				2.443	152.3	2.556	18.5	4.5		6,346	20.7

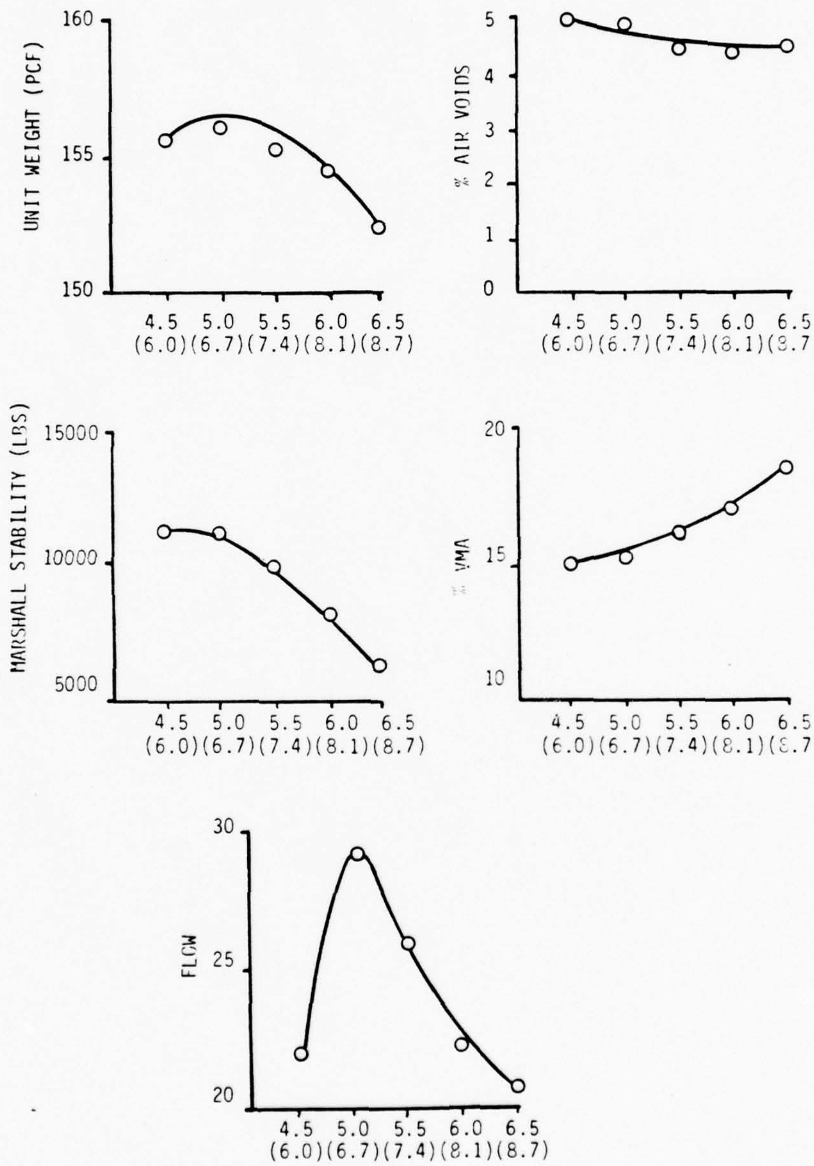


Figure 3.2. MARSHALL MIX DESIGN DATA CURVES
50/50 ASPHALT/SULPHUR RATIO

Table 3.4. MARSHALL MIX DESIGN DATA
70/30 ASPHALT SULPHUR RATIO

BINDER CONTENT (%) BY WEIGHT	SAMPLE	WEIGHT IN AIR (GRAMS)	WEIGHT IN WATER (GRAMS)	BULK SPECIFIC GRAVITY	UNIT WEIGHT	MAXIMUM SPECIFIC GRAVITY	VMA	% AIR VOIDS	STABILITY MEASURED	STABILITY ADJUSTED	FLOW
4.5	C_1	1249.0	738.5	2.447	152.9	2.687			4450	4851	17.8
(5.3)	C_2	1249.5	739.0	2.448	152.9	2.639			4780	5210	18.0
	C_3	1249.5	734.5	2.426	151.6	2.695			4700	5123	19.3
				2.440	152.5	2.674	16.7	8.6		5061	18.4
5.0	C_4	1261.5	749.5	2.464	153.5	2.665			5310	5788	19.7
(5.9)	C_5	1262.0	752.0	2.475	154.1	2.633			4660	5079	17.5
	C_6	1261.5	750.5	2.469	154.1	2.667			4920	5363	19.1
				2.469	153.9	2.652	16.3	7.0		5410	18.8
5.5	C_7	1258.0	755.0	2.501	156.0	2.623			4050	4415	20.0
(6.5)	C_8	1245.0	742.5	2.478	154.8	2.625			3980	4338	19.2
	C_9	1265.0	757.0	2.490	155.4	2.621			3140	3423	21.2
				2.490	155.4	2.623	16.0	5.1		4059	20.1
6.0	C_{10}	1254.0	748.5	2.481	154.8	2.612			2850	3249	20.6
(7.1)	C_{11}	1257.5	750.0	2.478	154.8	2.611			3600	4104	24.2
	C_{12}	1254.0	750.0	2.488	155.4	2.608			3600	3924	22.7
				2.482	155.0	2.610	16.6	4.9		3759	22.5
6.5	C_{13}	1261.5	753.0	2.481	154.8	2.600			3370	3673	28.9
(7.7)	C_{14}	1235.0	736.0	2.475	154.1	2.600			3200	3648	25.8
	C_{15}	1253.0	748.0	2.481	154.8	2.592			2770	3019	26.3
				2.479	154.6	2.597	17.3	4.7		3447	27.0

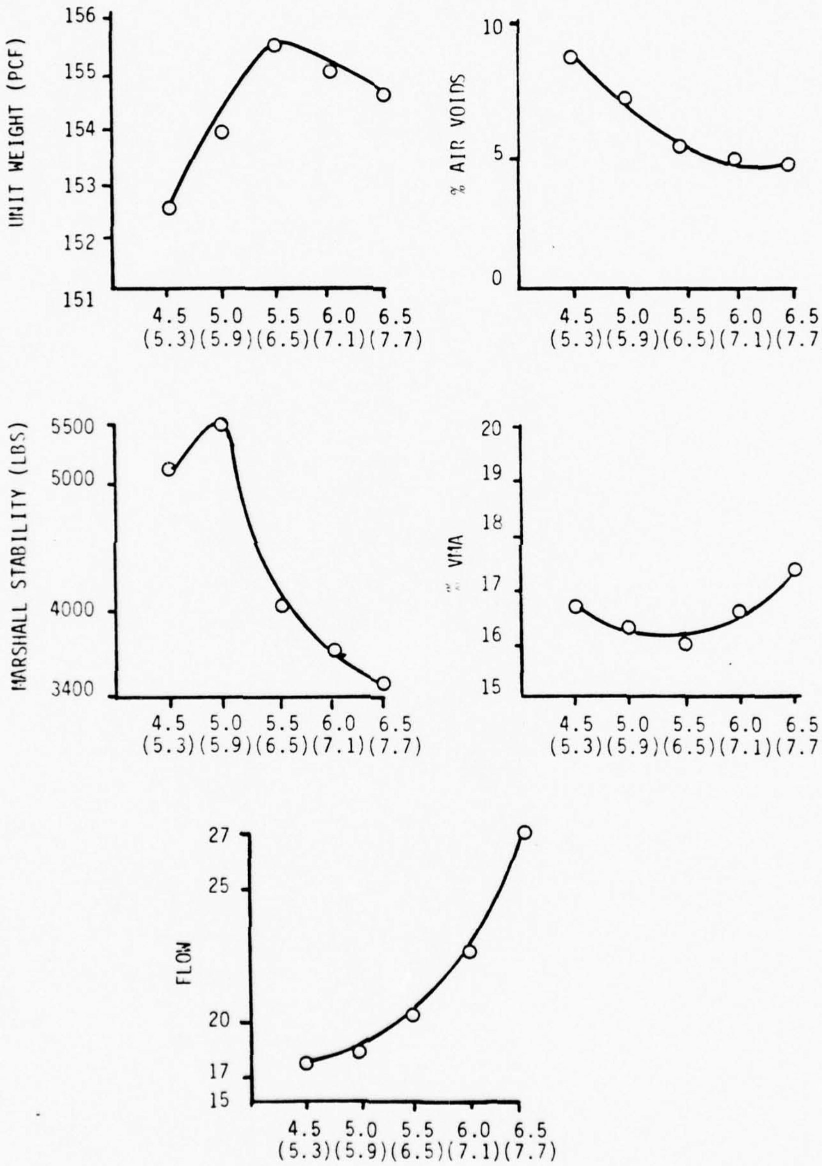


Figure 3.3. MARSHALL MIX DESIGN DATA CURVES
70/30 ASPHALT/SULPHUR RATIO

70/30 Asphalt Sulphur Ratio

Data Type	Value	Binder Content
Stability	5410-lb	5.0 (5.9)
Unit weight	155.4 pcf	5.5 (6.5)
Air voids	4.7%	6.5 (7.7)
Optimum binder content		5.7 (6.7)

The data curves for stability and unit weight are quite conclusive. The air voids curve, however, is not. There is a problem with high voids in the SEA samples. High voids are frequently, though not always, associated with high permeability. High permeability, by permitting circulation of air and water through the pavement, may lead to premature hardening of the binder. The voids can be reduced by increasing the mineral dust content of the mix. It may be necessary to combine the aggregates to more closely approximate the gradation of a maximum density grading curve (34). Consequently, the optimum binder content of the 50/50 and 70/30 binder ratio samples could be less by adjusting the aggregate and would then more closely resemble the conventional, 100/0, mix. Additionally, the compaction temperature is questioned. It is felt that the hardening of the sulphur during compaction has affected not only the void content and structure of the mixture, but also the stability.

The maximum unit weight data is very similar. The maximum value is reached at 5.0%, 5.0% and 5.5% for the 100/0, 50/50 and 70/30 binder ratios respectively. This is not surprising, although a wider spread might be expected due to the equivalent binder contents and the higher weights associated with the SEA samples.

The maximum stability values cover a large range. The maximum value is reached at 5.0%, 4.5% and 5.0% for the 100/0, 50/50 and 70/30 binder ratios respectively. The stabilities of the 100/0 and 70/30 samples are quite similar throughout the range of binder contents tested. The 50/50 stability, on the other hand, is very high. This could be caused, in part, by a "bridging" effect of the sulphur in the mixture during compaction due to the compaction temperature. This "bridging" effect can occur in two separate ways. First, since the samples are compacted close to the melting point of sulphur, the sulphur can solidify (harden) and form a crust on the outside of the sample, thus preventing the inner portion from receiving the uniform compaction of a conventional 100/0 sample. Secondly, as the sulphur solidifies and the compaction continues, the inner portion receives this equal compaction only after the outer crust has been "crushed" by the compaction. All SEA samples were observed to be very "crumbly" after compaction and cooling, and it is possible that both "bridging" effects could have occurred.

3.2 Hveem Method

3.2.1 Background

The Hveem mix design method was developed by Mr. Francis N. Hveem, formerly materials and research engineer for the California Division of Highways. This design method is based on the friction and cohesion of the pavement materials. The friction is evaluated by use of the Hveem stabilometer, which measures the horizontal pressure as a vertical pressure is applied (see Figure 2.10). The cohesion is tested by means of a cohesiometer, which measures the force

required to pull apart a test sample. In this study, only the stabilometer value was obtained because the stabilometer test is non-destructive and the cohesiometer is.

The Hveem samples were prepared and tested in accordance with Figures 2.4 and 2.6. The five binder content percentages tested were 4.0, 4.5, 5.0, 5.5 and 6.0 by total weight of the mix for the 100/0 samples; the equal weight percentages for the sulphur/asphalt binders are 5.4, 6.1, 6.7, 7.4 and 8.1 for the 50/50 SEA samples and 4.7, 5.3, 5.9, 6.5 and 7.1 for the 70.30 SEA samples. These percentages were obtained by evaluating the Marshall data. The data obtained on the 50/50 SEA Marshall samples was inconclusive below the 4.5 per cent binder content. All data on the higher binder contents, in all samples, appears to be conclusive. It was decided by the principals in this investigation to drop the Marshall binder content percentages by 0.5 per cent to investigate the results at 4.0 per cent binder content.

3.2.2 Results

The data obtained for the Hveem samples is presented in Tables 3.5 through 3.7 and Figures 3.4 through 3.6. The data used in the Hveem stabilometer value calculations is presented in Tables 3.8 through 3.10. Additionally, the indirect tensile strength data is presented in Tables 3.11 through 3.13 and Figure 3.7.

3.2.3 Discussion of Results

The results of the Hveem testing must be compared to standard criteria. The criteria are: stabilometer value of 35 or higher and

Table 3.5. HVEEM MIX DESIGN DATA
100/0 ASPHALT/SULPHUR RATIO

BINDER CONTENT (%) BY WEIGHT	SAMPLE	WEIGHT IN AIR (GRAMS)	WEIGHT IN WATER (GRAMS)	BULK SPECIFIC GRAVITY	UNIT WEIGHT	MAXIMUM SPECIFIC GRAVITY	% AIR VOIDS	STABILOMETER VALUE
4.0	D_1	1217.0	724.0	2.468				42.3
	D_2	1231.0	735.0	2.482				42.1
	D_3	1236.0	732.0	2.452				40.4
				2.467	153.9	2.665	8.1	41.6
4.5	D_4	1238.0	742.0	2.496				52.4
	D_5	1236.0	742.0	2.502				46.0
	D_6	1223.0	738.0	2.522				43.1
				2.507	156.4	2.619	4.2	47.1
5.0	D_7	1232.0	748.0	2.545				52.7
	D_8	1234.0	746.0	2.529				46.8
	D_9	1233.0	750.0	2.553				40.0
				2.542	1.587	2.591	1.6	46.5
5.5	D_{10}	1239.0	760.0	2.587				47.0
	D_{11}	1232.5	757.0	2.592				47.0
	D_{12}	1235.0	748.0	2.536				49.4
				2.572	160.6	2.587	0.5	47.8
6.0	D_{13}	1236.0	760.0	2.597				40.0
	D_{14}	1211.0	748.0	2.616				40.0
	D_{15}	1257.0	777.0	2.619				34.5
				2.611	163.1	2.614	0.04	38.2

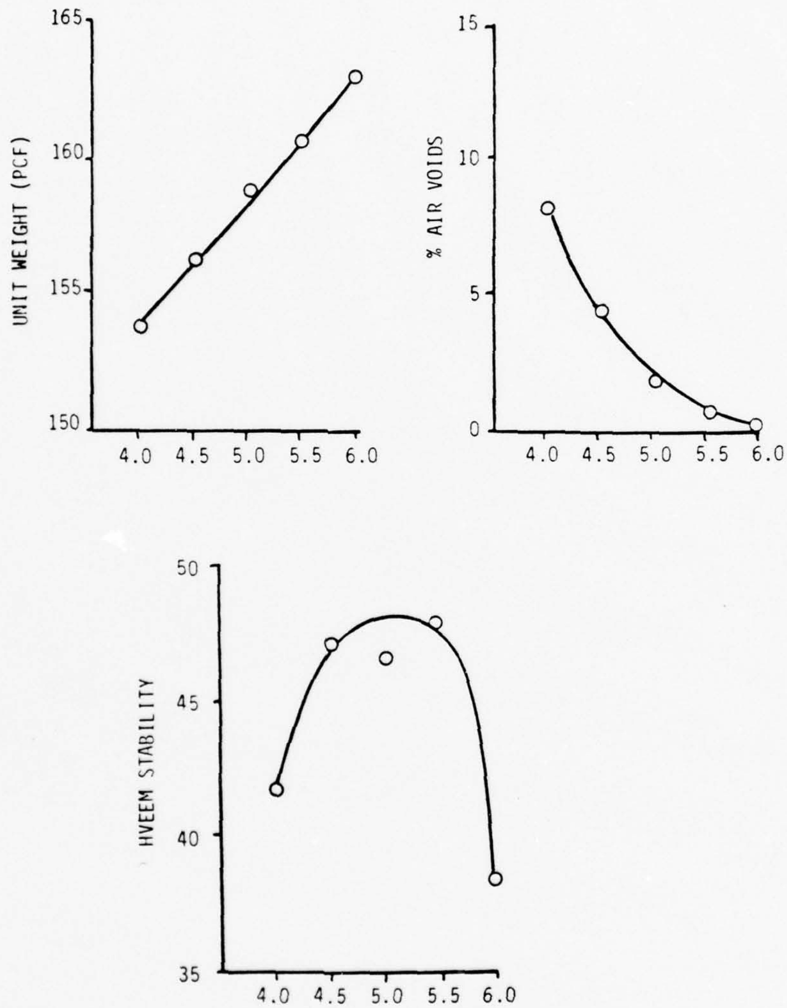


Figure 3.4. HVEEM MIX DESIGN DATA CURVES
100/0 ASPHALT/SULPHUR RATIO

Table 3.6. HVEEM MIX DESIGN DATA
50/50 ASPHALT/SULPHUR RATIO

BINDER CONTENT (%) BY WEIGHT	SAMPLE	WEIGHT IN AIR (GRAMS)	WEIGHT IN WATER (GRAMS)	BULK SPECIFIC GRAVITY	UNIT WEIGHT	MAXIMUM SPECIFIC GRAVITY	% AIR VOIDS	STABILO-METER VALUE
4.0 (5.4)	E_1	1241.0	736.0	2.458				58.6
	E_2	1248.0	740.0	2.457				63.0
	E_3	1243.0	736.0	2.452				55.4
				2.456	153.3	2.651	7.6	59.2
4.5 (6.1)	E_4	1261.0	752.0	2.477				62.4
	E_5	1257.0	755.0	2.504				64.8
	E_6	1248.0	746.0	2.486				65.0
				2.489	155.4	2.630	5.3	64.1
5.0 (6.7)	E_7	1254.0	753.0	2.503				62.1
	E_8	1243.0	741.0	2.476				59.7
	E_9	1244.0	743.0	2.483				61.6
				2.487	155.1	2.610	5.0	61.1
5.5 (7.4)	E_{10}	1263.0	770.0	2.562				65.2
	E_{11}	1266.0	766.0	2.532				69.7
	E_{12}	1258.0	764.0	2.547				65.3
				2.547	158.9	2.575	1.1	66.7
6.0 (8.1)	E_{13}	1242.0	760.0	2.577				65.0
	E_{14}	1265.0	774.0	2.576				66.1
	E_{15}	1243.0	754.0	2.542				52.7
				2.565	160.2	2.571	0.2	61.4

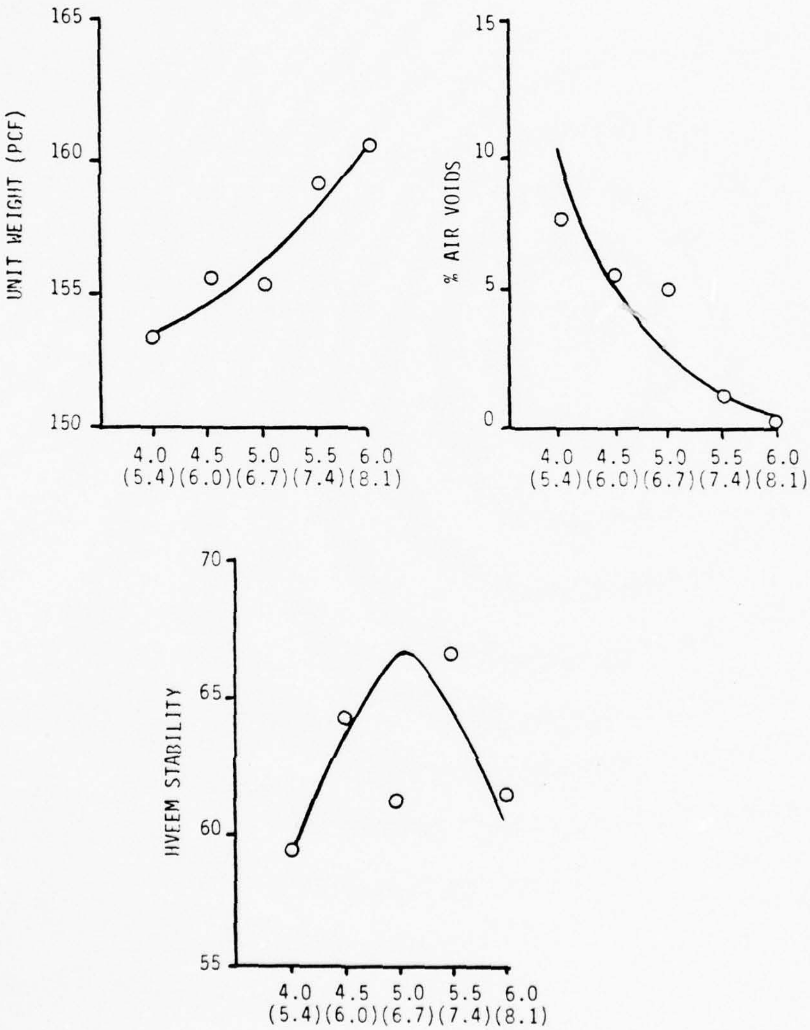


Figure 3.5. HVEEM MIX DESIGN DATA CURVES
50/50 ASPHALT/SULPHUR RATIO

Table 3.7. HVEEM MIX DESIGN DATA
70/30 ASPHALT/SULPHUR RATIO

BINDER CONTENT (%) BY WEIGHT	SAMPLE	WEIGHT IN AIR (GRAMS)	WEIGHT IN WATER (GRAMS)	BULK SPECIFIC GRAVITY	UNIT WEIGHT	MAXIMUM SPECIFIC GRAVITY	% AIR VOIDS	STABILOMETER VALUE
4.0 (4.7)	F_1	1233.0	732.0	2.461				47.0
	F_2	1236.0	731.0	2.448				52.4
	F_3	1238.0	737.0	2.471				40.4
				2.460	153.5	2.639	6.4	46.6
4.5 (5.3)	F_4	1249.0	755.0	2.528				51.1
	F_5	1237.0	742.0	2.499				47.5
	F_6	1246.0	753.0	2.527				52.6
				2.518	157.2	2.597	3.0	50.4
5.0 (5.9)	F_7	1243.0	757.0	2.558				50.9
	F_8	1252.0	759.0	2.540				55.6
	F_9	1248.0	759.0	2.552				51.7
				2.550	159.1	2.592	1.6	52.7
5.5 (6.5)	F_{10}	1262.0	771.0	2.570				49.9
	F_{11}	1236.0	756.0	2.575				53.6
	F_{12}	1254.5	763.0	2.552				53.2
				2.566	160.2	2.587	0.8	52.2
6.0 (7.1)	F_{13}	1249.0	772.0	2.618				48.3
	F_{14}	1254.0	773.0	2.607				52.6
	F_{15}	1252.0	763.0	2.560				51.1
				2.595	162.1	2.599	0.08	50.7

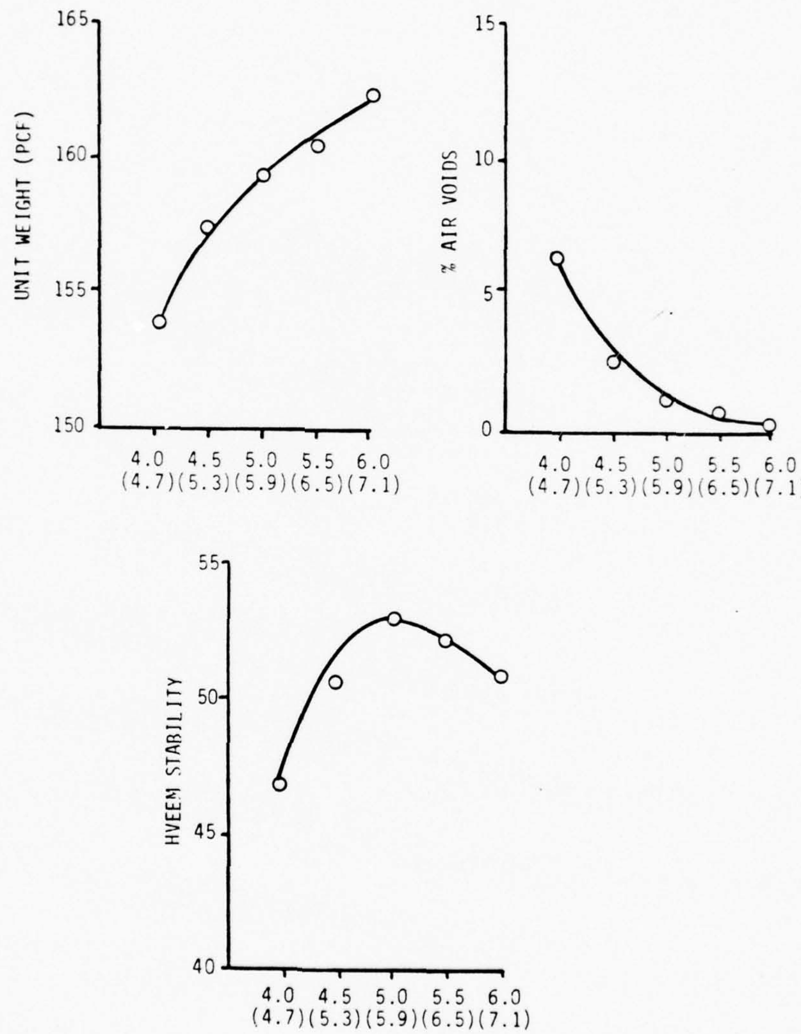


Figure 3.6. HVEEM MIX DESIGN DATA CURVES
70/30 ASPHALT/SULPHUR RATIO

Table 3.8. HVEEM STABILOMETER VALUES
100/0 ASPHALT SULPHUR RATIO

	PRESSURE (LB)								
SAMPLE	500	1000	2000	3000	4000	5000	6000	DISPL.	STABILO-METER VALUE
D_1	8	12	18	26	34	44	54	2.45	42.3
D_2	9	11	16	20	26	33	42	3.40	42.1
D_3	9	12	17	22	28	36	44	3.31	40.4
D_4	7	8	12	15	19	24	30	3.16	52.4
D_5	7	8	12	16	22	29	38	3.33	46.0
D_6	9	11	16	20	24	33	41	3.26	43.1
D_7	8	10	12	16	19	23	28	3.26	52.7
D_8	8	10	15	16	21	27	36	3.49	46.8
D_9	9	13	18	23	27	31	36	3.46	40.0
D_{10}	8	11	14	18	22	27	34	2.93	47.0
D_{11}	9	11	14	17	21	27	36	2.90	47.0
D_{12}	8	10	14	18	24	30	39	2.80	49.4
D_{13}	8	11	16	21	28	37	48	2.79	40.0
D_{14}	10	12	17	22	29	36	45	2.92	40.0
D_{15}	9	12	20	27	35	45	56	2.80	34.5

Table 3.9. HVEEM STABILOMETER VALUES
50/50 ASPHALT-SULPHUR RATIO

SAMPLE	PRESSURE (LB) 500	1000	2000	3000	4000	5000	6000	DISPL.	STABILOMETER VALUE
E_1	7	8	10	12	15	19	24	3.15	58.6
E_2	6	6	8	10	12	14	17	3.51	63.0
E_3	8	8	10	13	16	20	25	3.39	55.4
E_4	6	6	8	10	12	15	18	3.44	62.4
E_5	5	6	8	9	11	14	17	3.33	64.8
E_6	6	6	9	10	13	15	18	3.07	65.0
E_7	6	7	9	11	13	16	18	3.25	62.1
E_8	6	7	9	11	13	16	20	3.60	59.7
E_9	5	6	8	11	14	16	20	3.32	61.6
E_{10}	6	6	8	9	11	13	15	3.53	65.2
E_{11}	7	7	8	9	10	12	15	3.12	69.7
E_{12}	6	6	8	10	12	15	16	3.03	65.3
E_{13}	6	7	8	10	12	14	16	3.22	65.5
E_{14}	5	6	8	10	12	14	18	3.14	66.1
E_{15}	6	8	12	15	19	24	30	3.12	52.7

Table 3.10. HVEEM STABILOMETER VALUES
70/30 ASPHALT-SULPHUR RATIOS

SAMPLE	PRESSURE (LB) 500	1000	2000	3000	4000	5000	6000	DISPL.	STABILO-METER VALUE
F_1	8	10	14	19	23	29	35	3.20	47.0
F_2	8	9	11	14	17	23	29	3.31	52.4
F_3	8	11	15	20	24	33	42	3.64	40.4
F_4	7	9	12	15	19	25	31	3.19	51.1
F_5	6	8	12	17	21	27	33	3.39	47.5
F_6	7	8	9	14	18	22	26	3.43	52.6
F_7	7	9	12	15	19	24	29	3.35	50.9
F_8	6	8	11	14	17	21	26	3.20	55.6
F_9	6	8	12	16	21	26	33	2.98	51.7
F_{10}	7	9	14	19	23	30	37	2.75	49.9
F_{11}	8	10	13	17	20	25	30	2.88	53.6
F_{12}	7	8	12	15	20	24	30	3.06	53.2
F_{13}	7	9	14	19	24	30	37	2.93	48.3
F_{14}	8	10	13	17	21	25	33	3.00	52.6
F_{15}	7	9	13	16	20	26	33	3.06	51.1

method. Hence, a lower void content is found in the Hveem samples compared to the Marshall.

3.2.4 Indirect Tensile Strength

The indirect tensile strength (31, 32) was measured for all Hveem samples. This test is important since large tensile stresses may occur at the bottom of the pavement layer. If tensile strength is exceeded, cracking of the pavement layer will occur. Figure 3.7 graphically presents this data. In general, the tensile strengths do not increase with the addition of sulphur. As with the M_R (resilient modulus) values, the strengths from the lowest to highest are the 70/30, 100/0 and 50/50 binder ratios (Tables 3.11 - 3.13). This could be caused by the structure of the mixture. A small amount of sulphur changes the structure of the mixture to become weaker, whereas the addition of a large amount of sulphur increases the strength. As stated previously, the compaction temperature could have a significant effect on the results.

In contrast to the above testing done at 25°C (77°F), the No. 8 sample from each binder ratio was tested at 5°C (41°F). The addition of the sulphur caused a reduction in strength when compared to the 100/0 sample. This is due to the brittleness of the sulphur in the samples.

3.3 Comparison of Mix Design Results

The results of the Hveem and Marshall mix designs have been presented and discussed. In addition to the separate results, it is important to compare the results of the two methods. The optimum

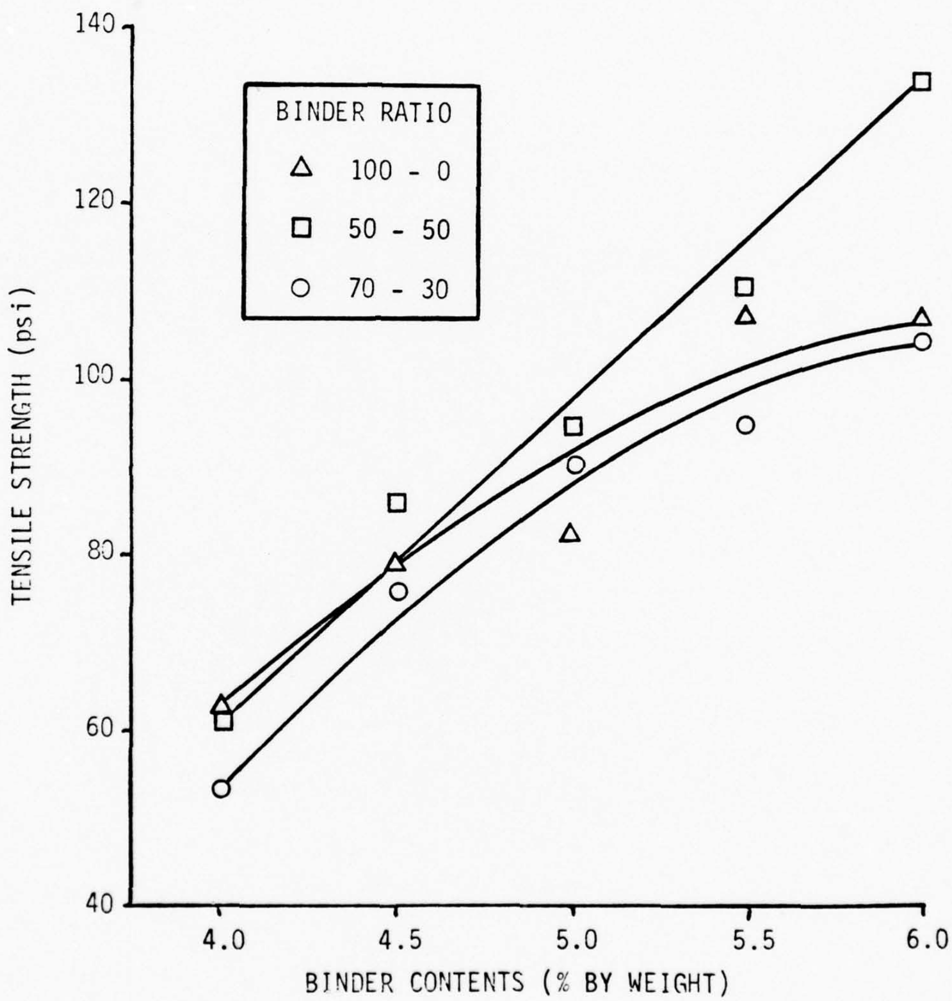


Figure 3.7 INDIRECT TENSILE STRENGTH (psi) AT VARIOUS ASPHALT/SULPHUR RATIOS

Table 3.11. INDIRECT TENSILE STRENGTH
100/0 ASPHALT-SULPHUR RATIO

SAMPLE	P_{MAX}	t	S_t	AVERAGE
D_1	890	2.44	58.1	
D_2	1090	2.44	71.1	62.7
D_3	925	2.50	58.9	
D_4	1285	2.44	83.8	
D_5	1125	2.44	73.4	79.0
D_6	1225	2.44	79.9	
D_7	1290	2.44	84.1	
*D_8	4850	2.44	308.8	82.4
D_9	1235	2.38	80.6	
D_{10}	1715	2.38	114.7	
D_{11}	1585	2.38	106.0	107.1
D_{12}	1540	2.44	100.5	
D_{13}	1535	2.32	105.3	
D_{14}	1575	2.32	108.0	107.3
D_{15}	1585	2.32	108.7	

*D_8 was tested at 5°C (41°F) and is not included in the average.

Table 3.12. INDIRECT TENSILE STRENGTH
50/50 ASPHALT-SULPHUR RATIO

SAMPLE	P_{MAX}	t	S_t	AVERAGE
E_1	1100	2.50	70.0	
E_2	1125	2.50	71.6	60.2
E_3	615	2.50	39.0	
E_4	1335	2.50	85.0	
E_5	1430	2.50	91.0	85.9
E_6	1285	2.50	81.8	
E_7	1455	2.50	92.6	
*E_8	3950	2.50	251.5	94.9
E_9	1525	2.50	97.1	
E_{10}	1765	2.50	112.4	
E_{11}	1560	2.50	99.3	110.6
E_{12}	1840	2.44	120.0	
E_{13}	2125	2.38	142.1	
E_{14}	2375	2.44	154.9	134.5
E_{15}	1635	2.44	106.6	

*E_8 was tested at 5°C (41°F) and is not included in the average.

Table 3.13. INDIRECT TENSILE STRENGTH
70/30 ASPHALT-SULPHUR RATIO

SAMPLE	P_{MAX}	t	S_t	AVERAGE
F_1	790	2.50	50.3	
F_2	1020	2.50	64.9	52.9
F_3	685	2.50	43.6	
F_4	1120	2.50	71.3	
F_5	1170	2.50	74.5	75.7
F_6	1245	2.44	81.2	
F_7	1330	2.44	86.8	
*F_8	4000	2.44	254.7	90.2
F_9	1435	2.44	93.6	
F_{10}	1550	2.38	103.7	
F_{11}	1170	2.38	78.2	95.0
F_{12}	1580	2.44	103.1	
F_{13}	1465	2.38	98.0	
F_{14}	1570	2.38	105.0	104.7
F_{15}	1705	2.44	111.2	

*F_8 was tested at 5°C (41°F) and is not included in the average.

approximately 4% (minimum) air voids (35). The binder content is determined by graphing the results and comparing them to the above criteria. Additionally, a .3% reduction in binder content to allow for variation in plant production is used to determine the optimum binder content (29).

The results for this determination for each asphalt/sulphur ratio binder are presented below:

<u>100/0 Asphalt/Sulphur Ratio</u>

Data Type	Value	Binder Content
Air voids	Approx. 4.0	4.6
Stability	47.1	4.5
Optimum binder content (4.6 - .3)		4.3

<u>50/50 Asphalt/Sulphur Ratio</u>

Data Type	Value	Binder Content
Air voids	Approx. 4.0	5.1 (6.9)
Stability	61.1	5.0 (6.7)
Optimum binder content (5.0 - .3)		4.8 (6.5)

<u>70/30 Asphalt/Sulphur Ratio</u>

Data Type	Value	Binder Content
Air voids	Approx. 4.0	4.4 (5.2)
Stability	50.4	4.5 (5.3)
Optimum binder content (4.4 - .3)		4.1 (4.8)

The optimum binder contents are lower than those of the Marshall samples (approximately 0.5% less) and is probably due to the compaction method. The kneading compaction does not allow a crust to form on the outside of the sample and cause the "bridging" effect discussed in the Marshall section. Additionally, this compaction method achieved higher densities for the mixtures tested than the Marshall

binder content summary is presented in Table 3.14. The results show a lower optimum binder content for the Hveem mix design samples, presumably due to the difference in compaction methods. The kneading compaction achieves a higher density in the samples and the 4% air voids content occurs at a lower binder content.

The results of the stabilities concur with other investigations (3, 9, 10, 12, 13, 14, 15, 23, 37). In general, the more sulphur added, the higher the stability (Figures 3.8 and 3.9). It is interesting to note that the 100/0 and 70/30 binder ratio results are quite similar in shape and magnitude. This could be an indication that they exhibit the same characteristics in a field environment. The 50/50 samples, on the other hand, achieve much higher stabilities. It appears that the sulphur is having more of an effect on the sample than the asphalt. This could lead to severe cracking problems during hot/cold temperature cycles.

Although flow is not measured for Hveem samples, a discussion of the Marshall flow values is necessary. The flow values achieved in this study are very high and do not fall in the range of acceptable values. Other investigations (3, 10, 13, 14, 15, 23, 37) have shown the flow values of SEA samples to be similar to conventional, 100/0, samples. Therefore, the flow values and experimental testing device used in this study are questioned.

The optimum asphalt binder content recommended to the Washington State Department of Transportation was 5.5% of equivalent binder volume for the various binder ratios. This was based on a close analysis

Table 3.14 SUMMARY OF MARSHALL AND HVEEM LABORATORY MIX DESIGNS

Binder Ratio	Optimum Binder Content	
	Marshall Mix Design	Hveem Mix Design
1. S/A: 0/100		
(a) Unit Weight	5.0%	-
(b) Air Voids	5.0%	4.6%
(c) Marshall Stability	5.0%	-
(d) Hveem Stability	-	4.5%
2. S/A: 50/50		
(a) Unit Weight	5.0% (6.7)	-
(b) Air Voids	6.0% (8.1)	5.1% (6.8)
(c) Marshall Stability	4.5% (6.1)	-
(d) Hveem Stability	-	5.0% (6.7)
3. S/A: 30/70		
(a) Unit Weight	5.5% (6.5)	-
(b) Air Voids	6.5% (7.7)	4.4% (5.2)
(c) Marshall Stability	5.0% (5.9)	-
(d) Hveem Stability	-	4.5% (5.3)

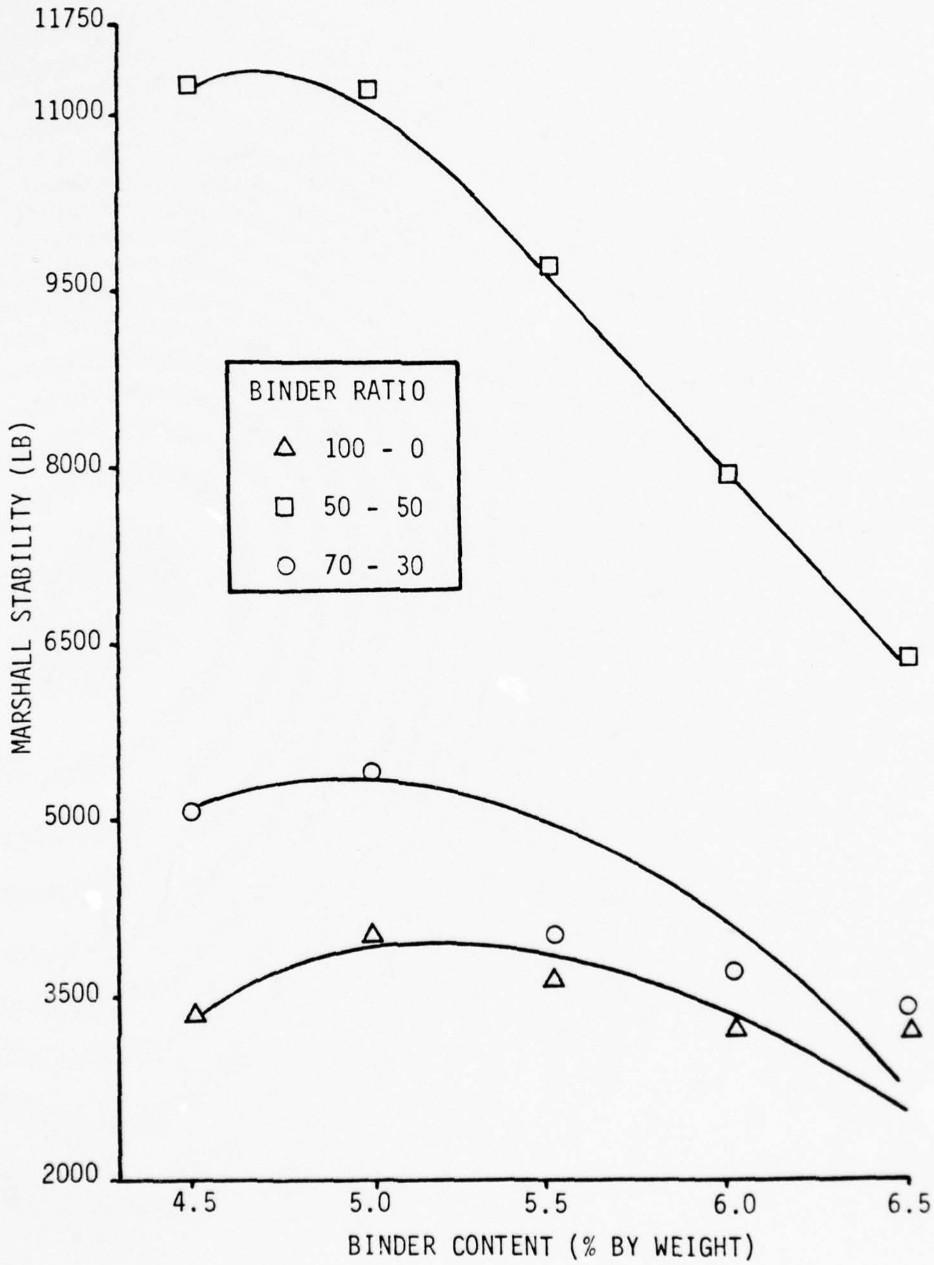


Figure 3.8 COMPARISON OF MARSHALL STABILITIES OF VARIOUS ASPHALT/SULPHUR RATIO SAMPLES

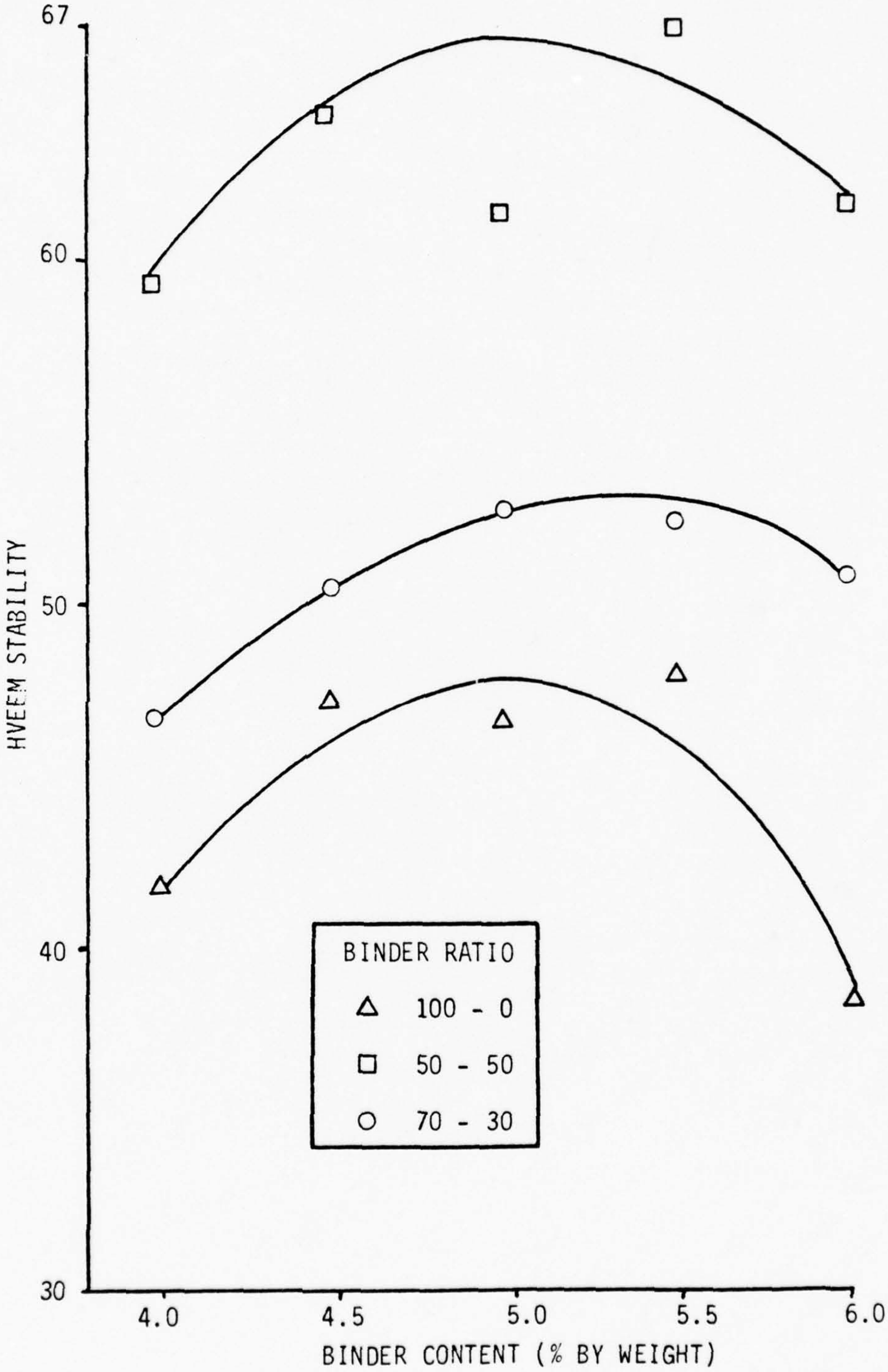


Figure 3.9 COMPARISON OF HVEEM STABILITIES OF VARIOUS ASPHALT/SULPHUR RATIO SAMPLES

of all laboratory data and the knowledge that the optimum binder content for field conditions are often higher than obtained by use of laboratory data. It was learned after the recommendation that historical data on the in situ pavement mixtures using the same aggregate and asphalt show the optimum binder content to range between 5.5% and 6.0% (36).

The issue of a mix design to obtain an optimum binder content raises a very interesting question. In this age of energy and materials conservation, should the mix design be based on an optimum binder content or another criterion such as equal strength? In this study, the stabilities achieved were quite high. Knowing that the air voids can be controlled to some degree by the gradation of the aggregate and the uncertainty as to the value of selecting the mixture with the highest unit weight, a stability meeting the minimum criteria could be selected. However, there might be a problem with the durability of the pavement due to the low binder content. This must be investigated before a final decision on equal strengths is made. It is very possible that the conventional mix designs, designed when asphalt was plentiful, should be revised or new mix designs developed to conserve asphalt. In addition, the relative effectiveness of the conventional mix designs is suspect when unusual materials are used as a substitute or extender.

CHAPTER IV

RESILIENT MODULUS

4.1 Background

The resilient modulus (M_R) is a dynamic test response defined as the ratio of the repeated axial deviator stress to the recoverable axial strain. The test may be conducted on all types of pavement materials ranging from cohesive to stabilized materials (32).

An indirect test for measuring the tensile strength of Portland cement concrete (PCC) was described in 1953 by Carniero and Barcellus in Brazil (38), and independently by Akazawa (39) in Japan. In this test, cylinders of PCC were crushed by applying uniformly distributed loads along two opposite generatrices. It was shown by mathematical analyses (40,41) (assuming plane stress) that a uniform compressive load applied perpendicularly to the horizontal diametral plane of a thin disk gives rise to a uniform tensile stress over the vertical diametral plane containing the applied load. A simplified mathematical treatment was given by Frocht (4) who supported his mathematics by photoelastic analyses of plastic disks.

When the approach used above is applied to dynamically loaded disks or cylinders, it is possible to determine the elastic modulus of the material. This is accomplished by measuring the elastic deformation across the diameter resulting from the application of a load along the vertical diameter (42).

In this study, the M_R was tested on each sample for seven consecutive days. Results of all M_R testing is presented in Appendix B. Each sample was loaded on two diametral axes and the average deformation was used to calculate the M_R using the formula stated in Chapter 2. The temperature of the samples during this testing was 25°C (77°F). Upon completion of testing at this temperature, the samples were then tested at 5°C (41°F) and 40°C (104°F) to determine the M_R value versus the function of temperature.

Poisson's ratio was also determined daily for each sample. The vertical deformation was measured with a non-recording dial guage. The calculated Poisson's ratio values are presented in Appendix D. Due to the gross variation in the Poisson's ratio values, the method and particularly the dial guage used to obtain the deformation is questioned. Subsequently, no calculated Poisson's ratio values were used in determining any M_R values. The Poisson's ratio value used in this study was selected as .3.

4.2 Results

The results of the M_R values obtained at 25°C (77°F) have been graphically contoured and are presented in Figures 4.1 through 4.6. The cross section of the various binder ratio M_R values of the Hveem samples at 5.5% binder content is shown in Figure 4.7. The M_R values obtained as a function of temperature are presented in Figure 4.8 through 4.17.

4.3 Discussion of Results

4.3.1 Constant Temperature Contours

The contouring of the M_R values has provided very interesting and unique information. The Marshall samples do not appear to exhibit any general trends. Each of the binder ratios has a different contour pattern. These patterns could be caused by a number of reasons. The "bridging" or crusting action has already been discussed in the stability section and could, again, be one reason. Another reason could be the change in the structure of the mixture after the sulphur was added. The amount of free sulphur, whether well dispersed or concentrated in an area, would have a very pronounced effect on the M_R results. Additionally, this free sulphur could also affect the void content and void structure in the mix.

A close look at the Marshall contouring does reveal one similarity, however. The highest M_R value for each binder ratio occurs at 4.5% binder content. Additionally, it is found that the order of M_R values from lowest to highest is 70/30, 100/0 and 50/50. It is interesting to note that the addition of a small amount of sulphur decreases the M_R value, whereas the addition of a large amount increases the M_R value significantly. In addition, the compaction temperature could have a significant effect on the M_R values due to the premature hardening of the sulphur during compaction. The structure of the mixture and the void percentage must be changed significantly for this to occur.

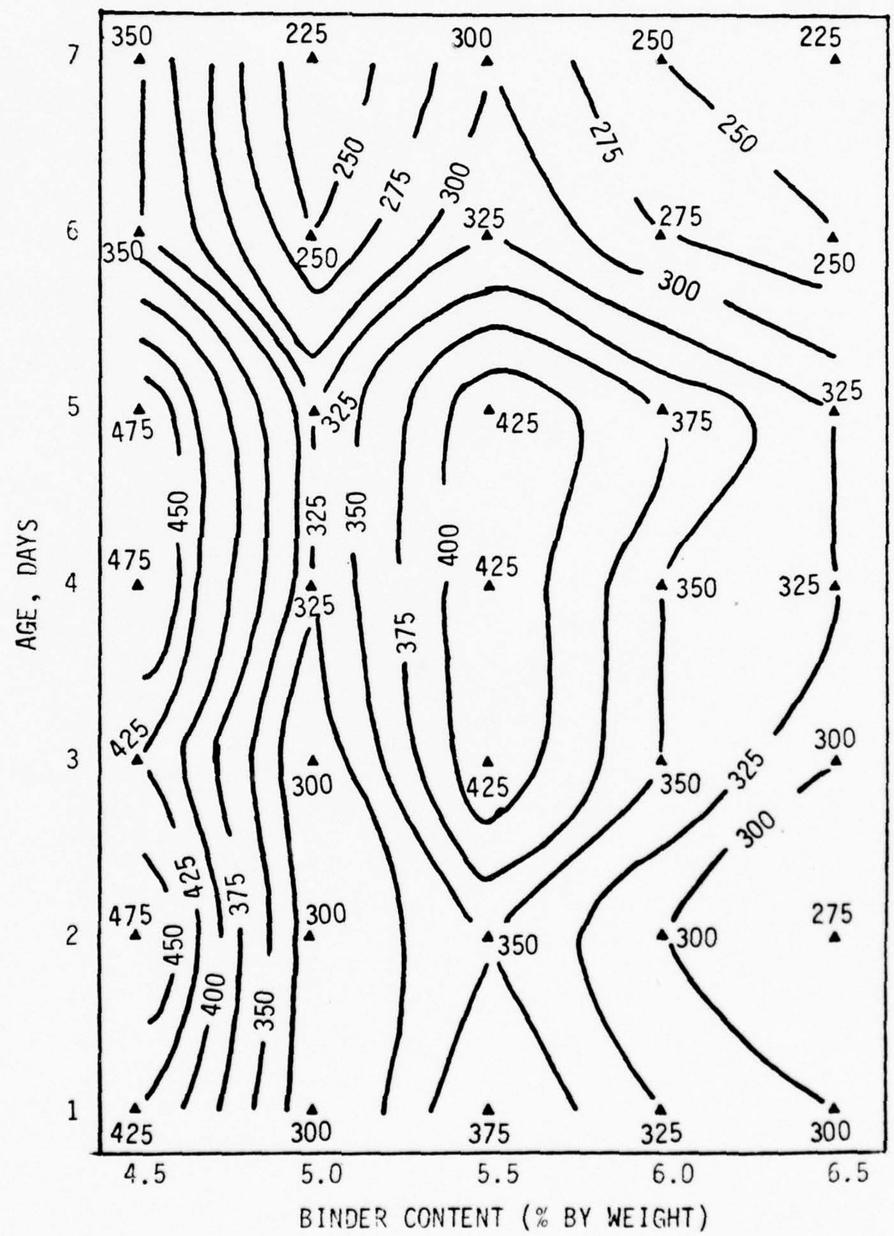


Figure 4.1 M_R VS BINDER CONTENT AND DAYS OF CURE AT 25°C (77°F) MARSHALL SAMPLES, 100/0 ASPHALT/SULPHUR RATIO

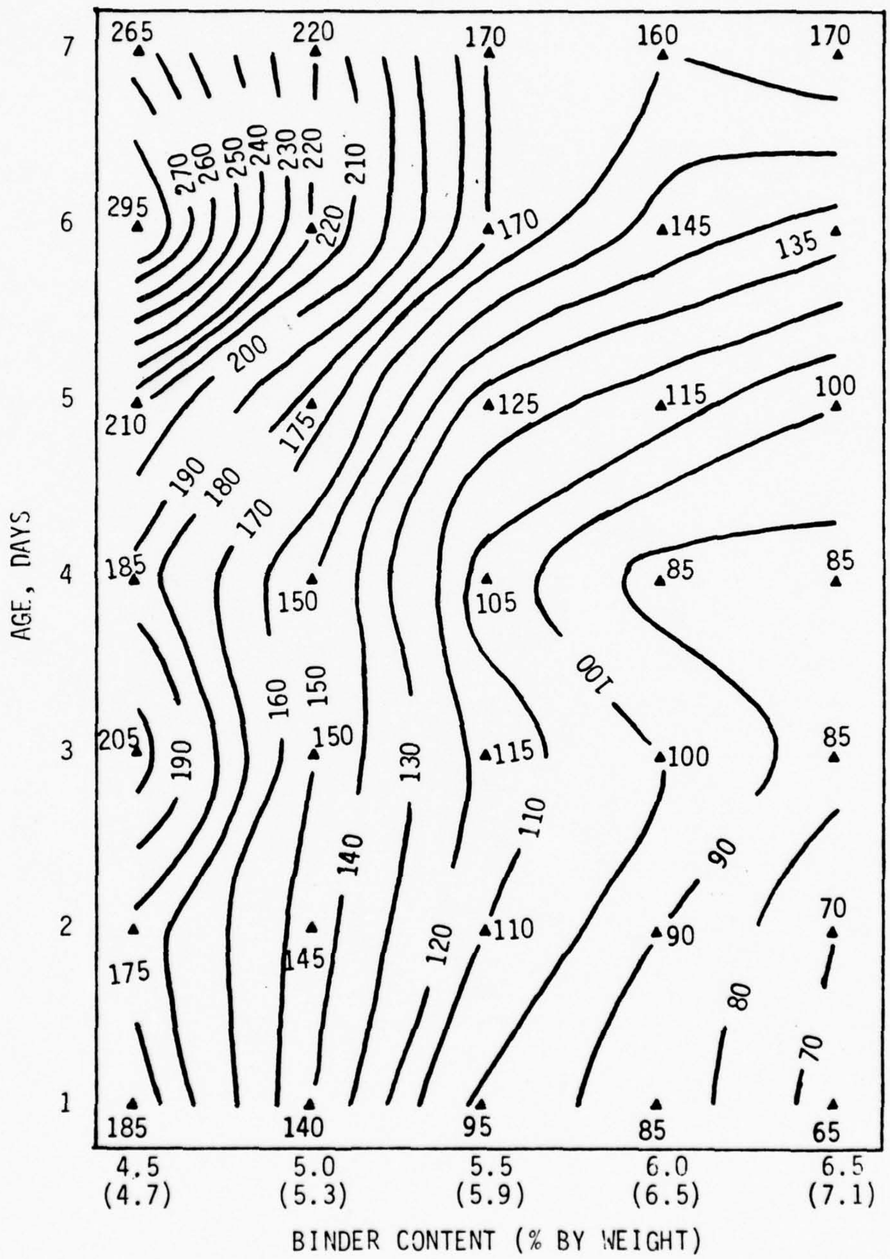


Figure 4.3 M_R VS BINDER CONTENT AND DAYS OF CURE AT 25°C (77°F) MARSHALL SAMPLES, 70/30 ASPHALT/SULPHUR RATIO

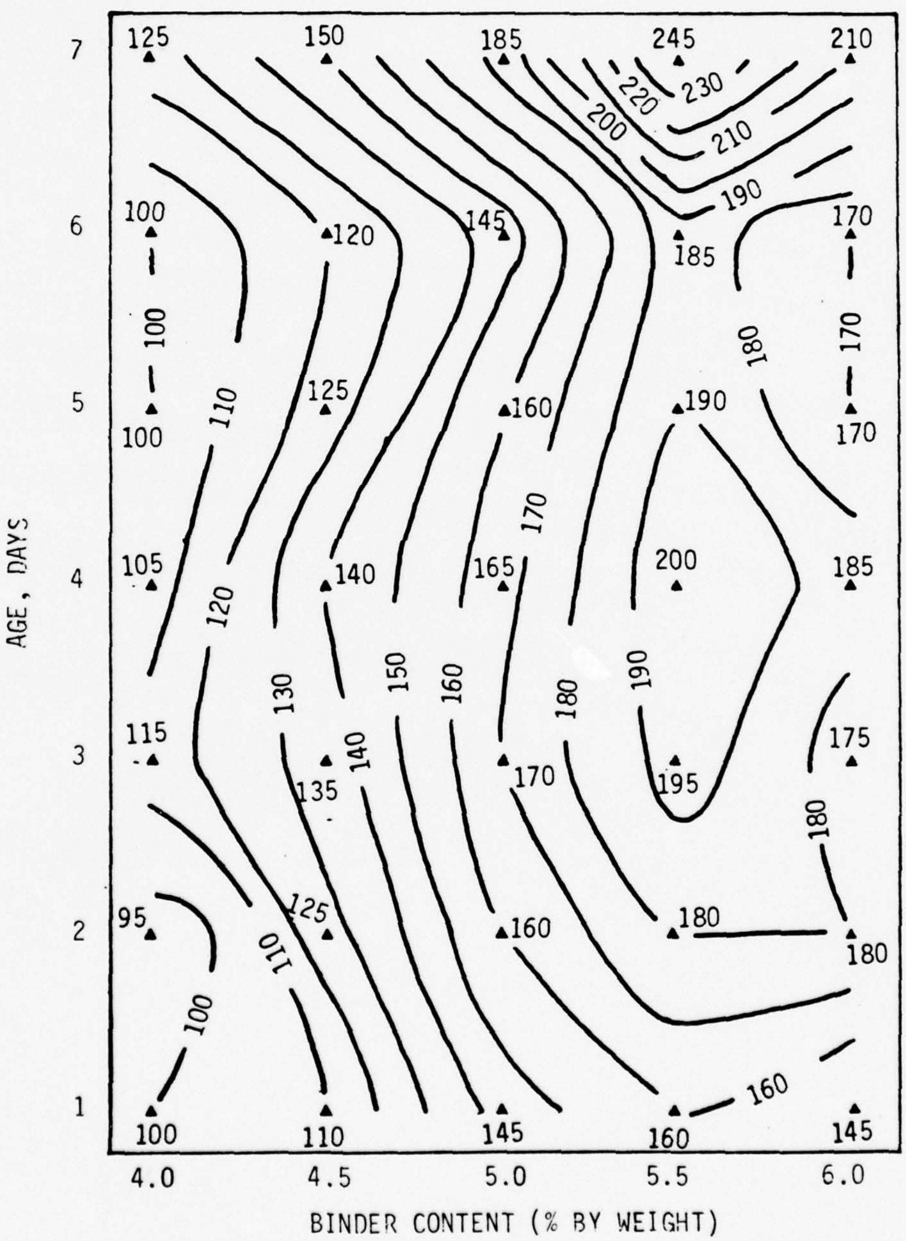


Figure 4.4 M_R VS BINDER CONTENT AND DAYS OF CURE AT 25°C (77°F) HVEEM SAMPLES, 100/0 ASPHALT/SULPHUR RATIO

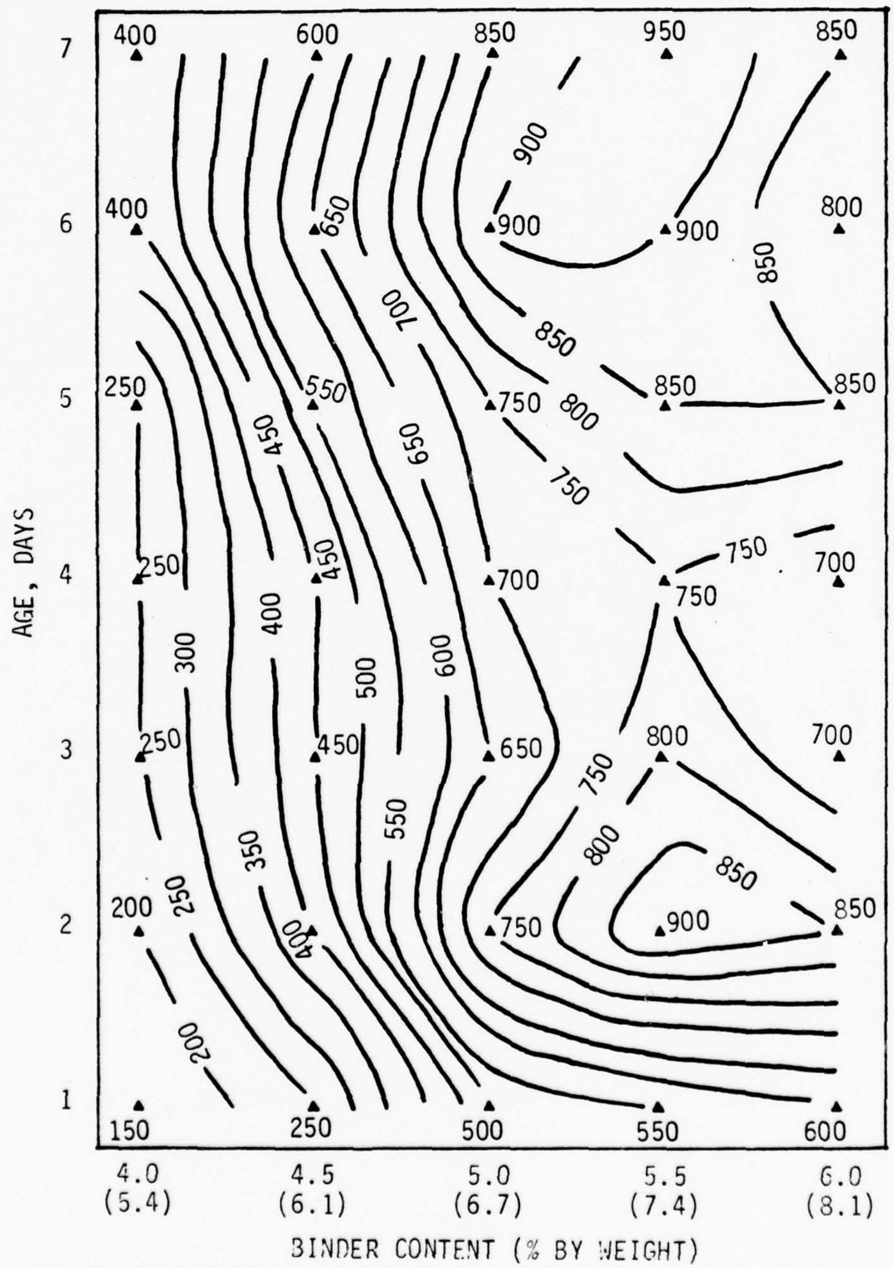


Figure 4.5 M_R VS BINDER CONTENT AND DAYS OF CURE AT 25°C (77°F) HVEEM SAMPLES, 50/50 ASPHALT/SULPHUR RATIO

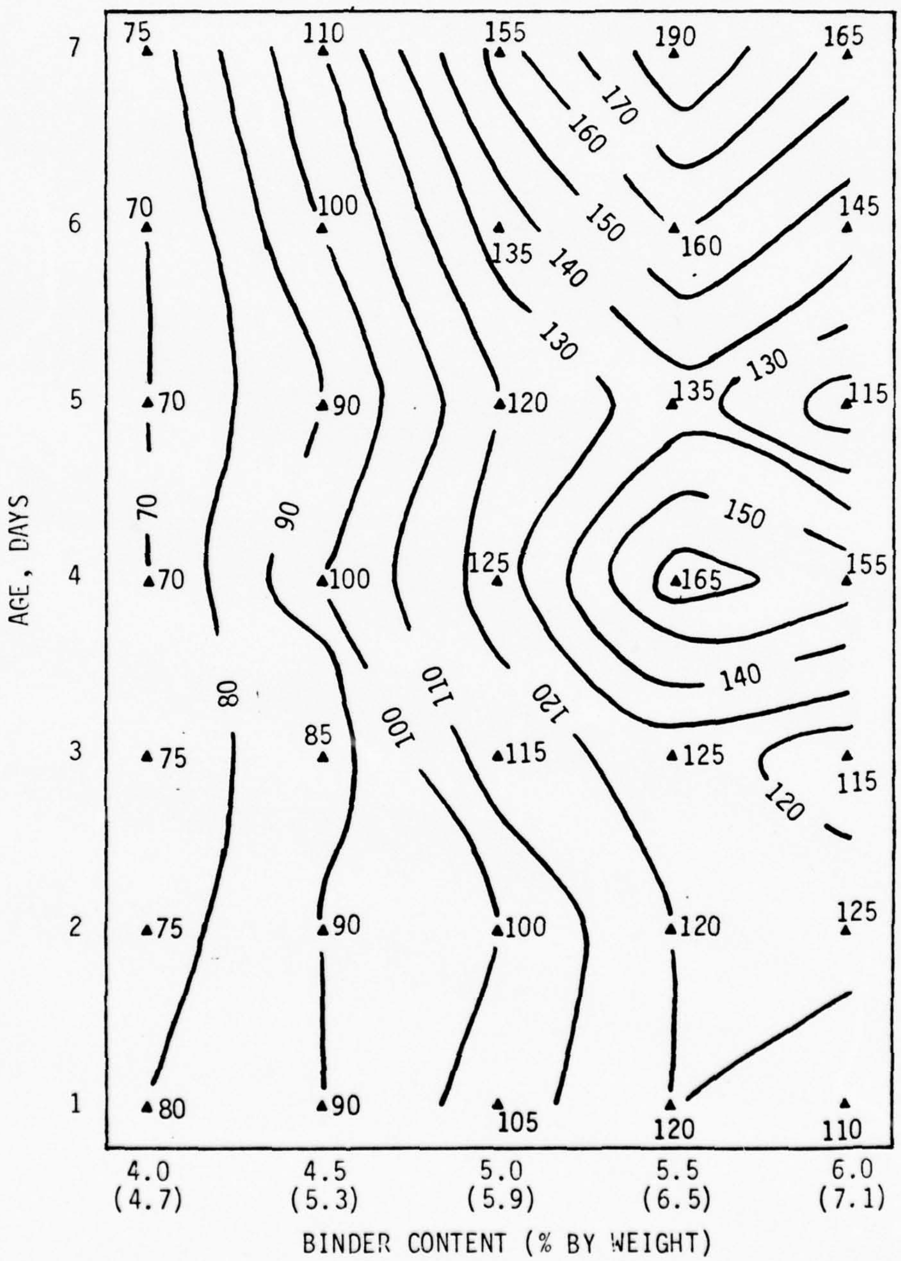


Figure 4.6 M_R VS BINDER CONTENT AND DAYS OF CURE AT 25°C (77°F) HVEEM SAMPLES, 70/30 ASPHALT/SULPHUR RATIO

The Hveem samples, as opposed to the Marshall, exhibit a very definite pattern. Regardless of the binder ratio, the maximum M_R value is obtained at 5.5% binder content. Figure 4.7 shows a cross section of the M_R values of the Hveem samples at 5.5% binder content. The different binder ratios show similar cross sections. As with the Marshall samples, this cound be caused by a variety of reasons including the structure of the mixture, the void content, effect of free sulphur. However, a more obvious effect is that of compaction. In the Marshall samples, the "hammering" effect of that compaction method appears to have caused a "crushing" of the outer crust. The Hveem compaction method, due to its kneading action, seems to preclude this and shows a uniform contour pattern between binder ratios. Overall, the M_R values for the Hveem samples are lower than for the Marshall. Thus the structure does not appear to have the chance to harden before compaction. It is highly significant that the optimum binder content recommended was the same binder content that obtained the highest resilient modulus for the different Hveem binder ratio samples.

4.3.2 Varied Temperature Curves

The resilient modulus value provides an estimate of the modulus of elasticity for a material at a specific temperature. The temperature is important since the M_R value is a function of temperature. As stated previously, on day 7 each sample was tested for M_R at 5°C (41°F), 25°C (77°F) and 40°C (104°F). Both of the mix designs show similar curves. The 50/50 binder ratio samples have a relatively

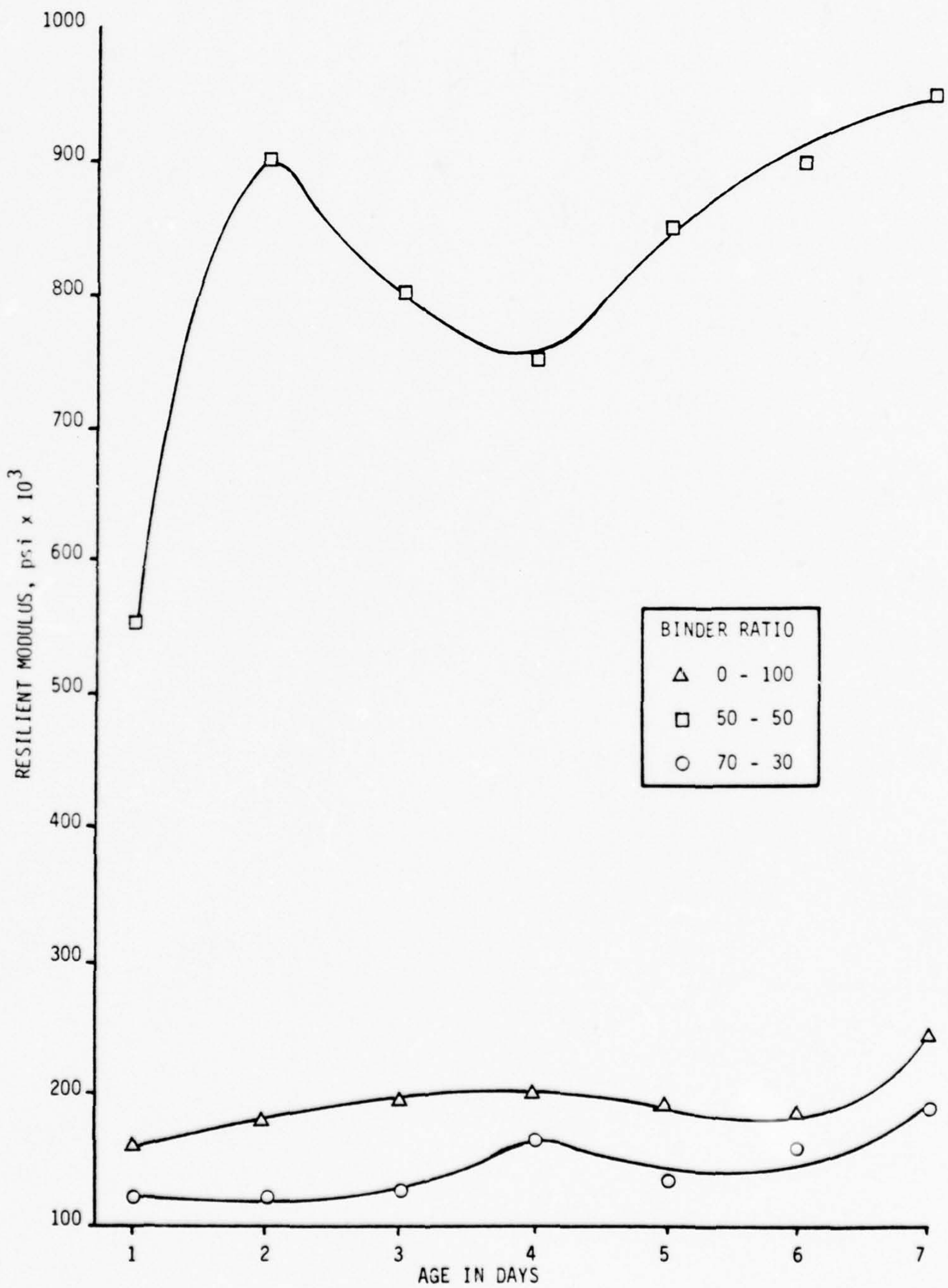


Figure 4.7 CROSS SECTION OF M_R VALUES OF HVEEM SAMPLES AT 5.5% BINDER CONTENT

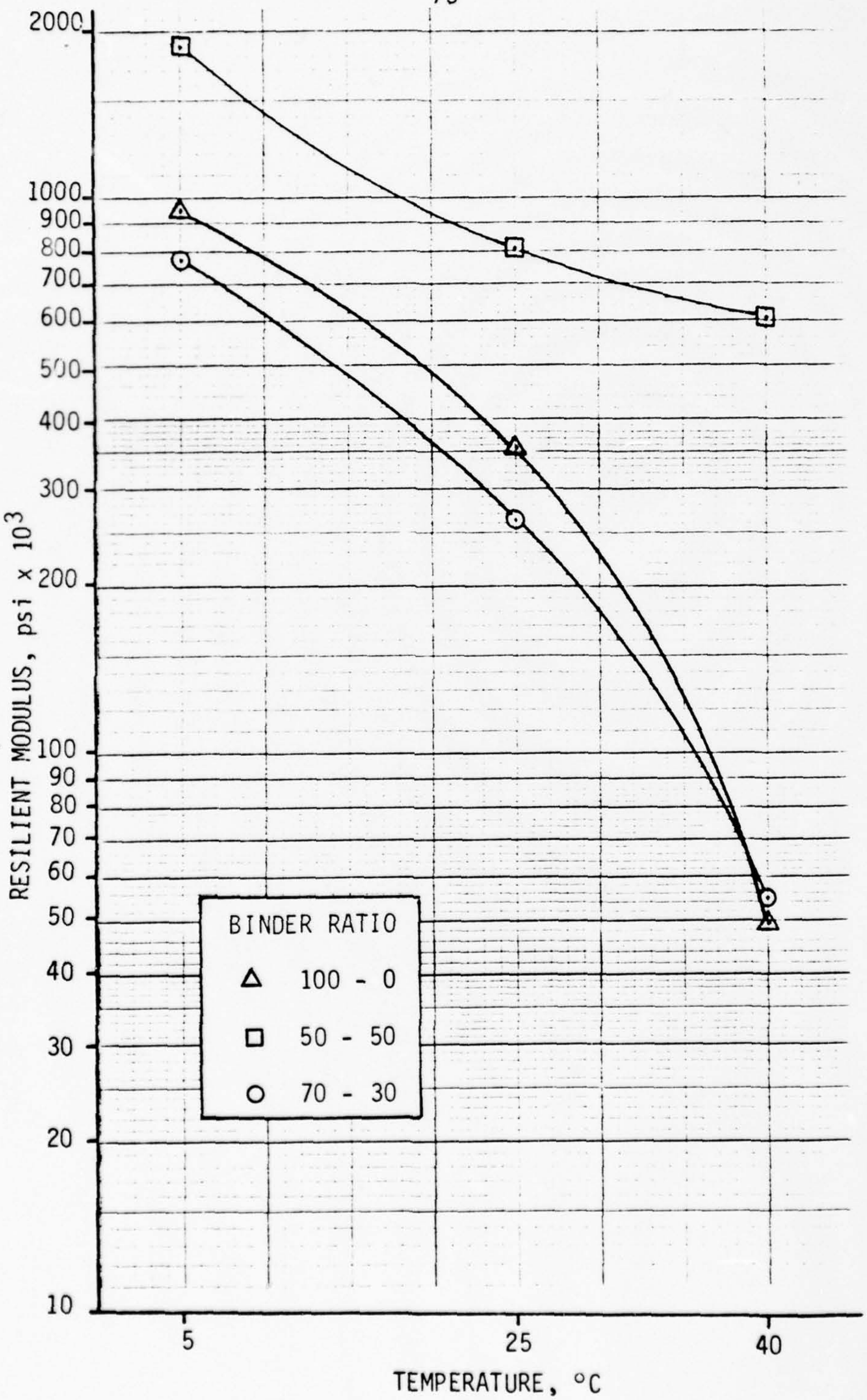


Figure 4.8 4.5% BINDER CONTENT, M_R VS TEMPERATURE: MARSHALL SAMPLES

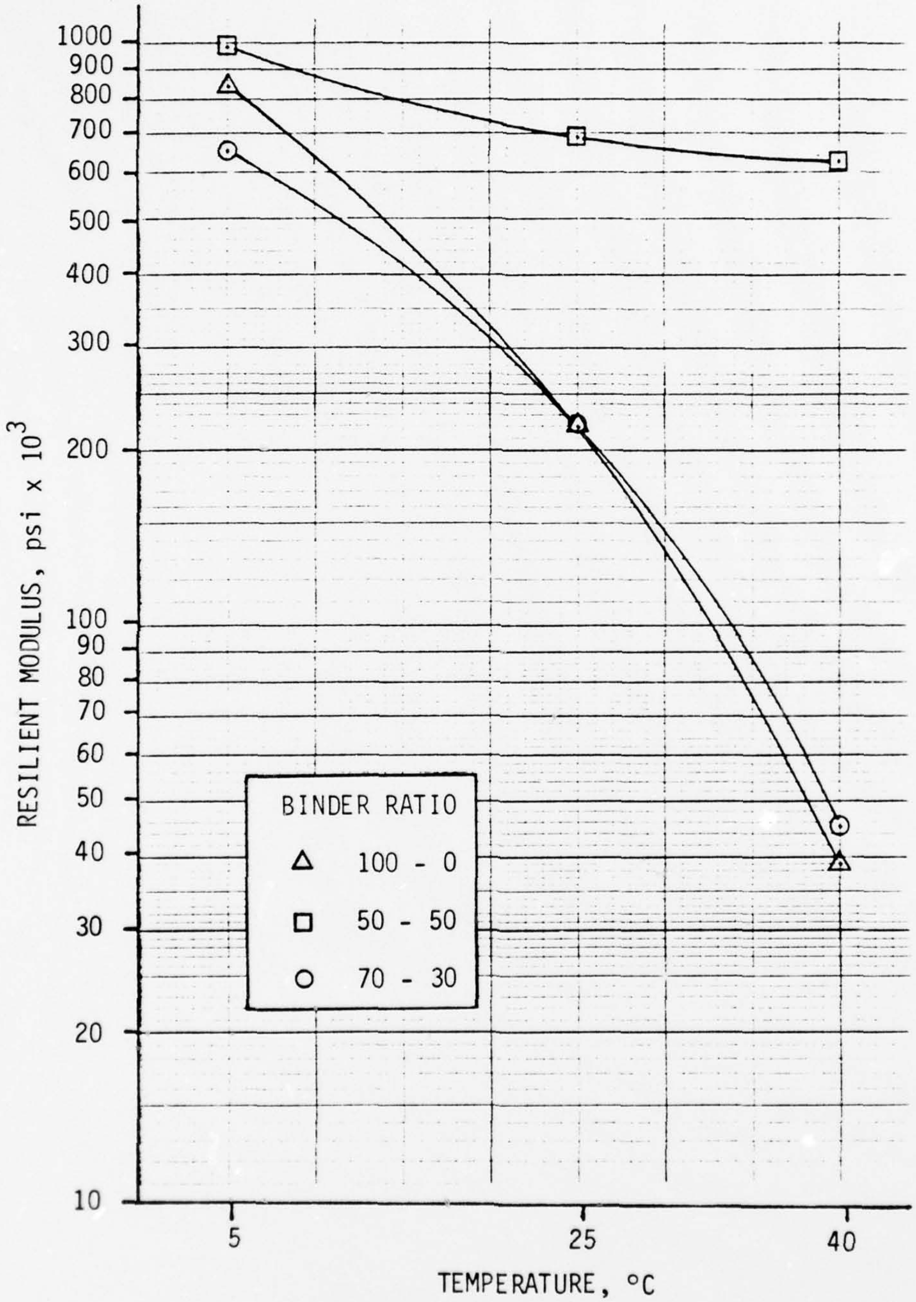


Figure 4.9 5.0% BINDER CONTENT, M_R VS TEMPERATURE: MARSHALL SAMPLES

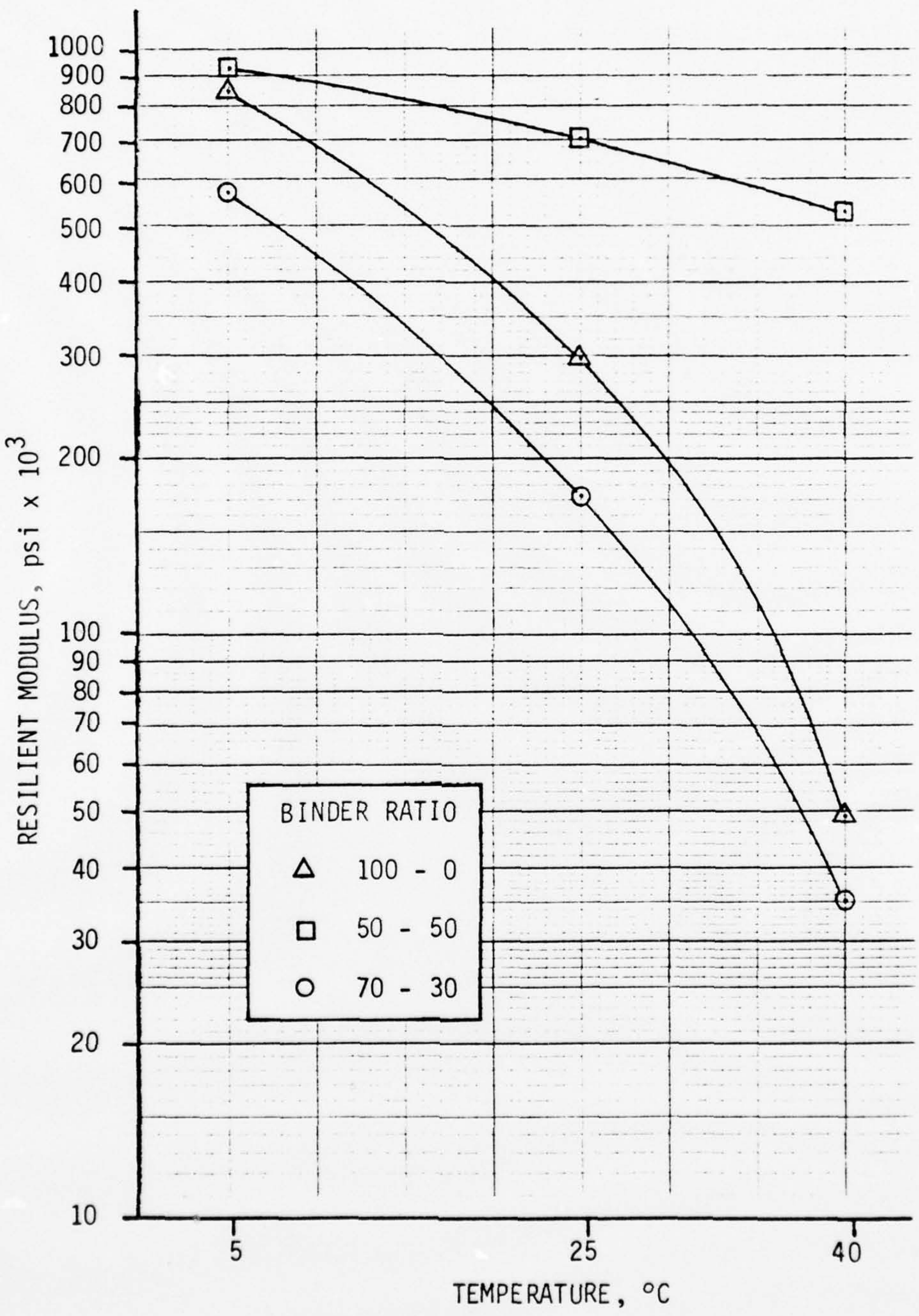


Figure 4.10 5.5% BINDER CONTENT, M_R VS TEMPERATURE: MARSHALL SAMPLES

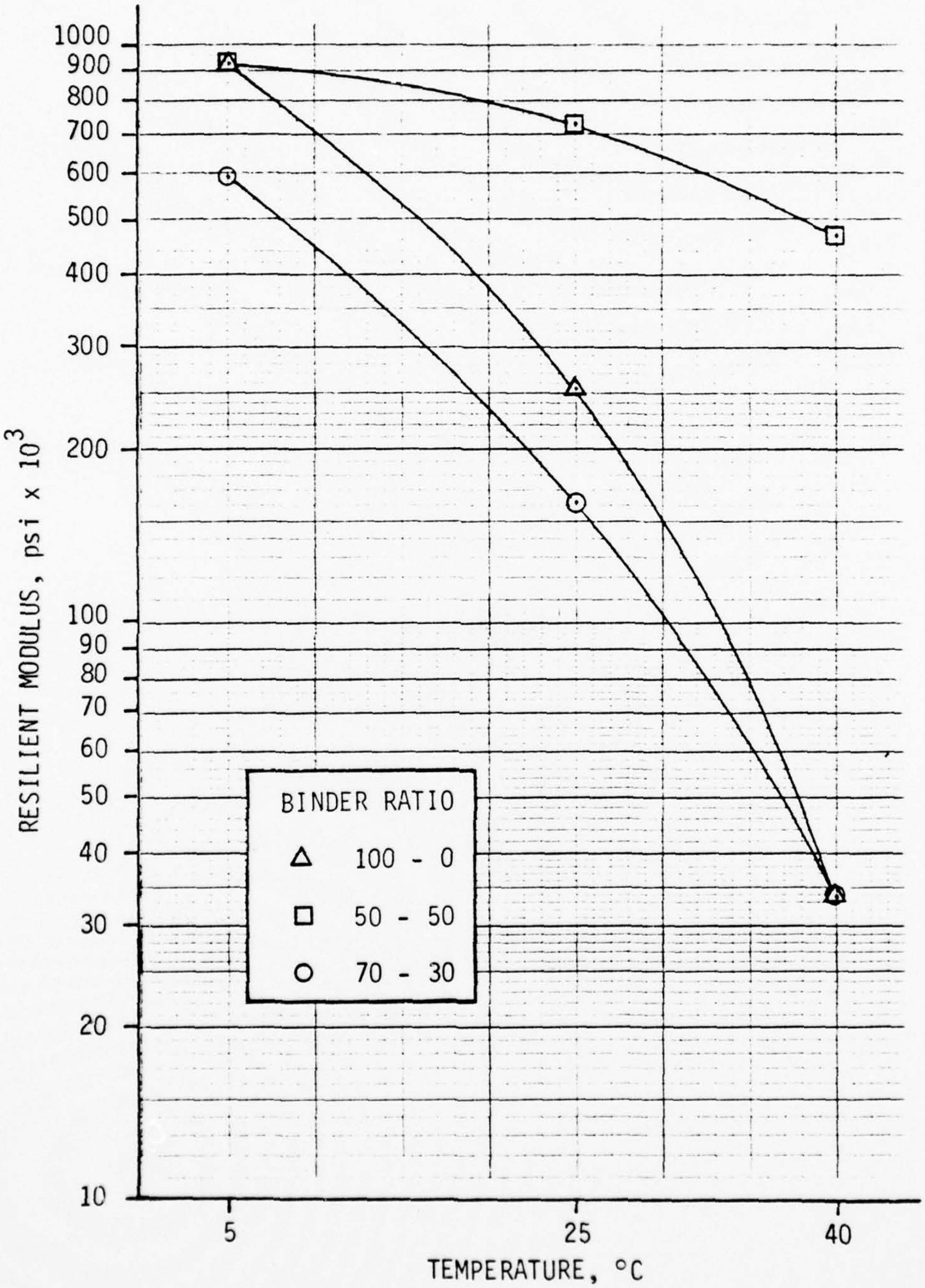


Figure 4.11 6.0% BINDER CONTENT, M_R VS TEMPERATURE: MARSHALL SAMPLES

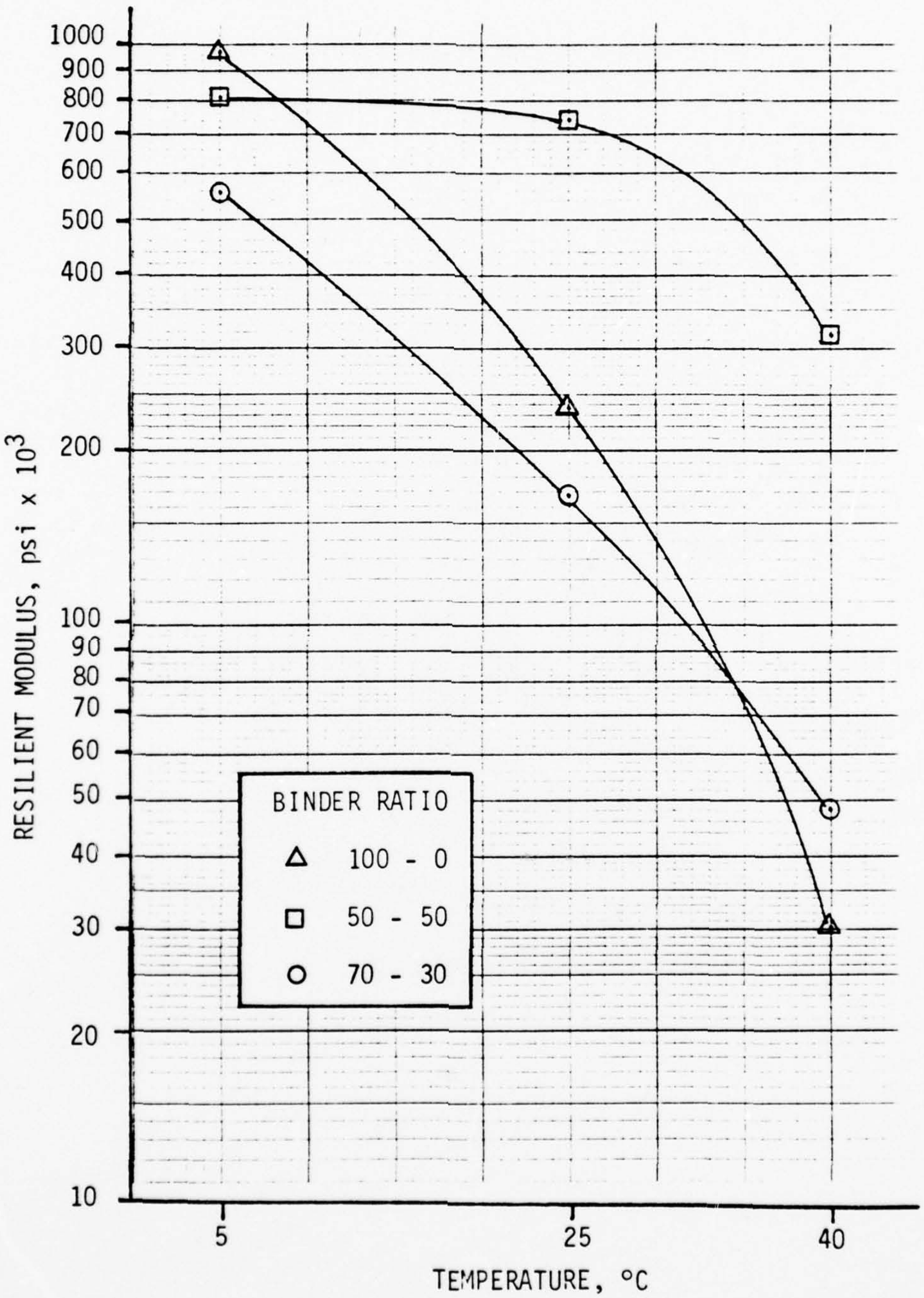


Figure 4.12 6.5% BINDER CONTENT, M_R VS TEMPERATURE: MARSHALL SAMPLES

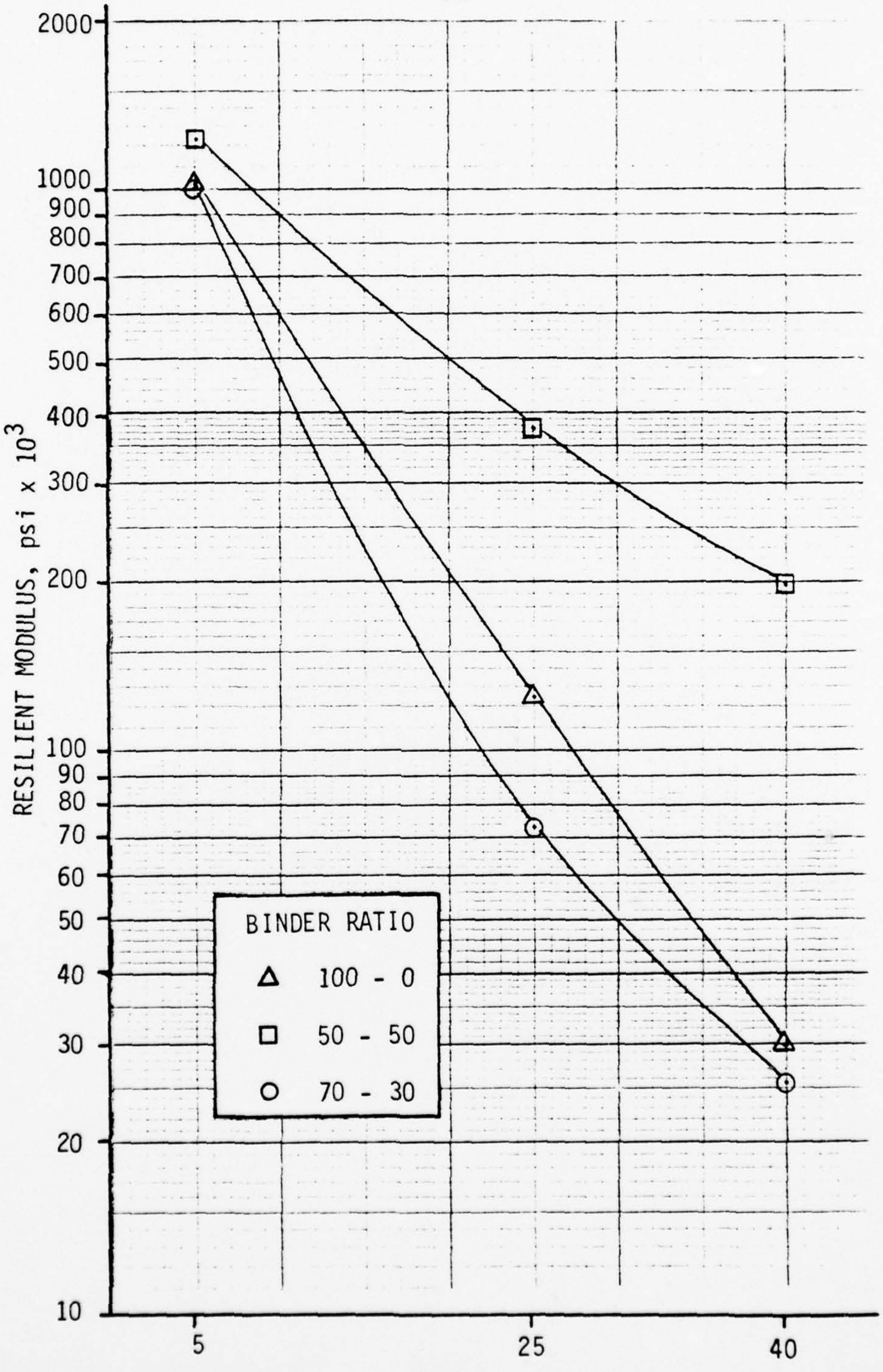


Figure 4.13 4.0% BINDER CONTENT, M_R VS TEMPERATURE: HVEEM SAMPLES

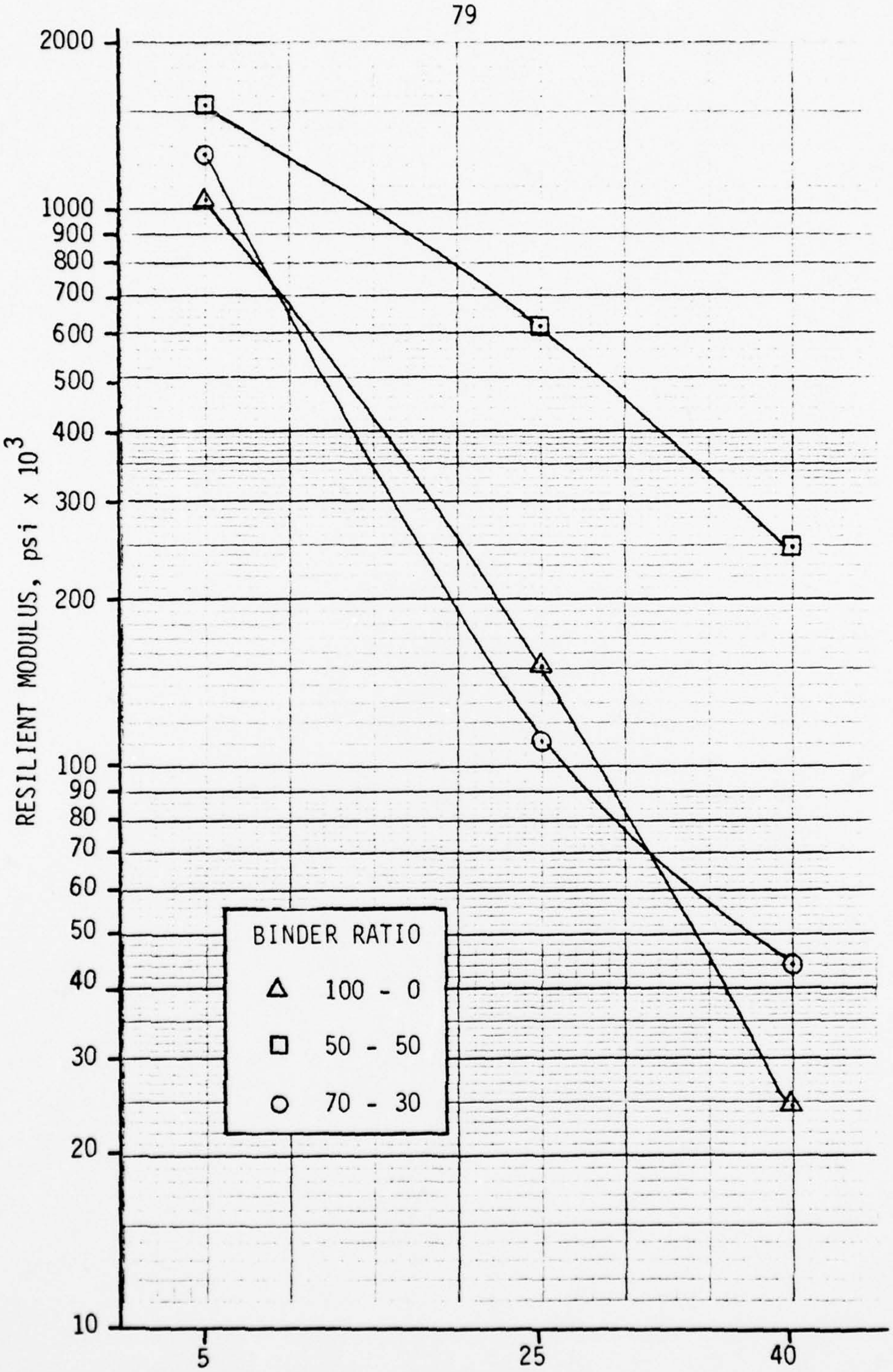


Figure 4.14 4.5% BINDER CONTENT, M_R VS TEMPERATURE: HVEEM SAMPLES

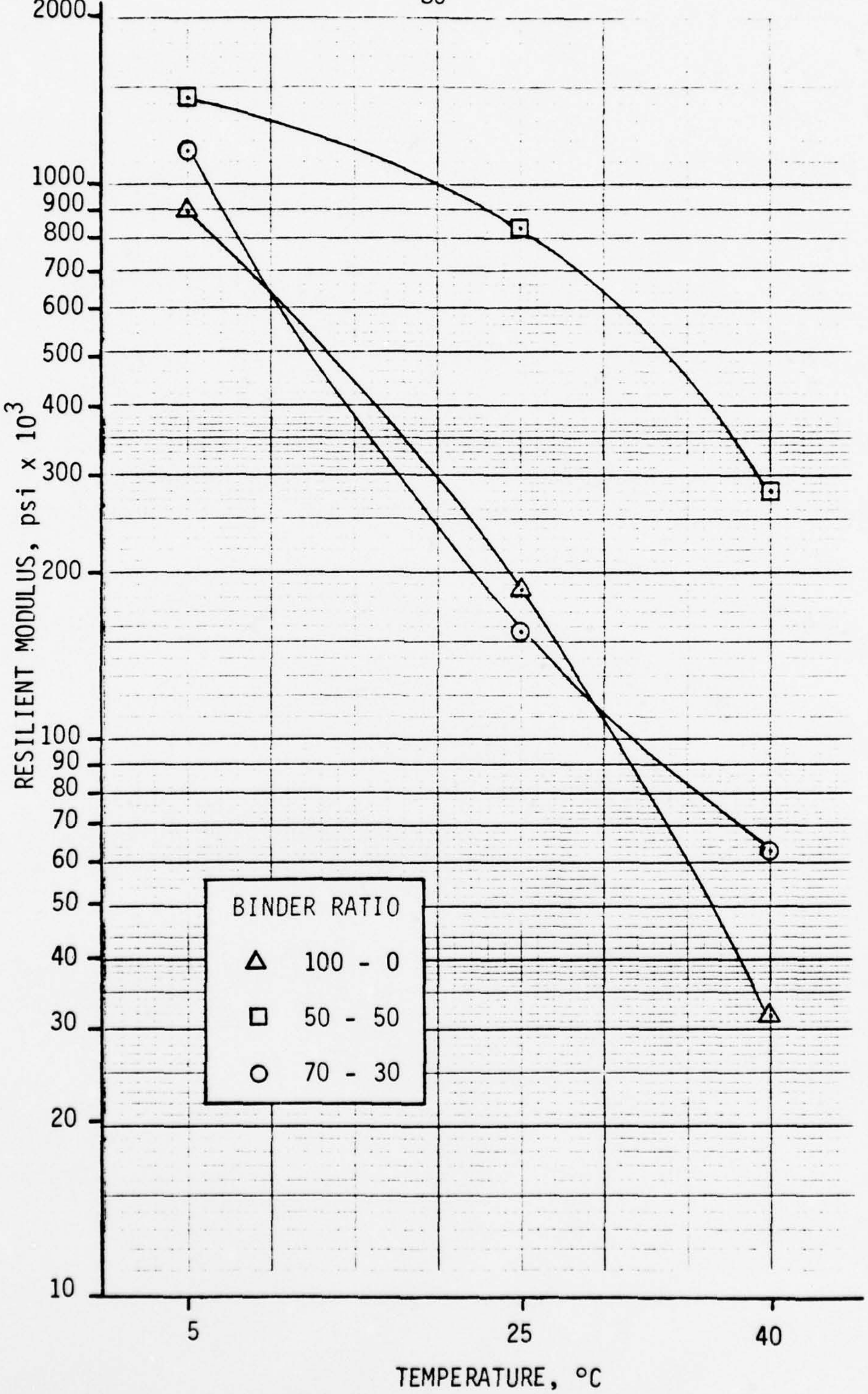


Figure 4.15 5.0% BINDER CONTENT, M_R VS TEMPERATUREL HVEEM SAMPLES

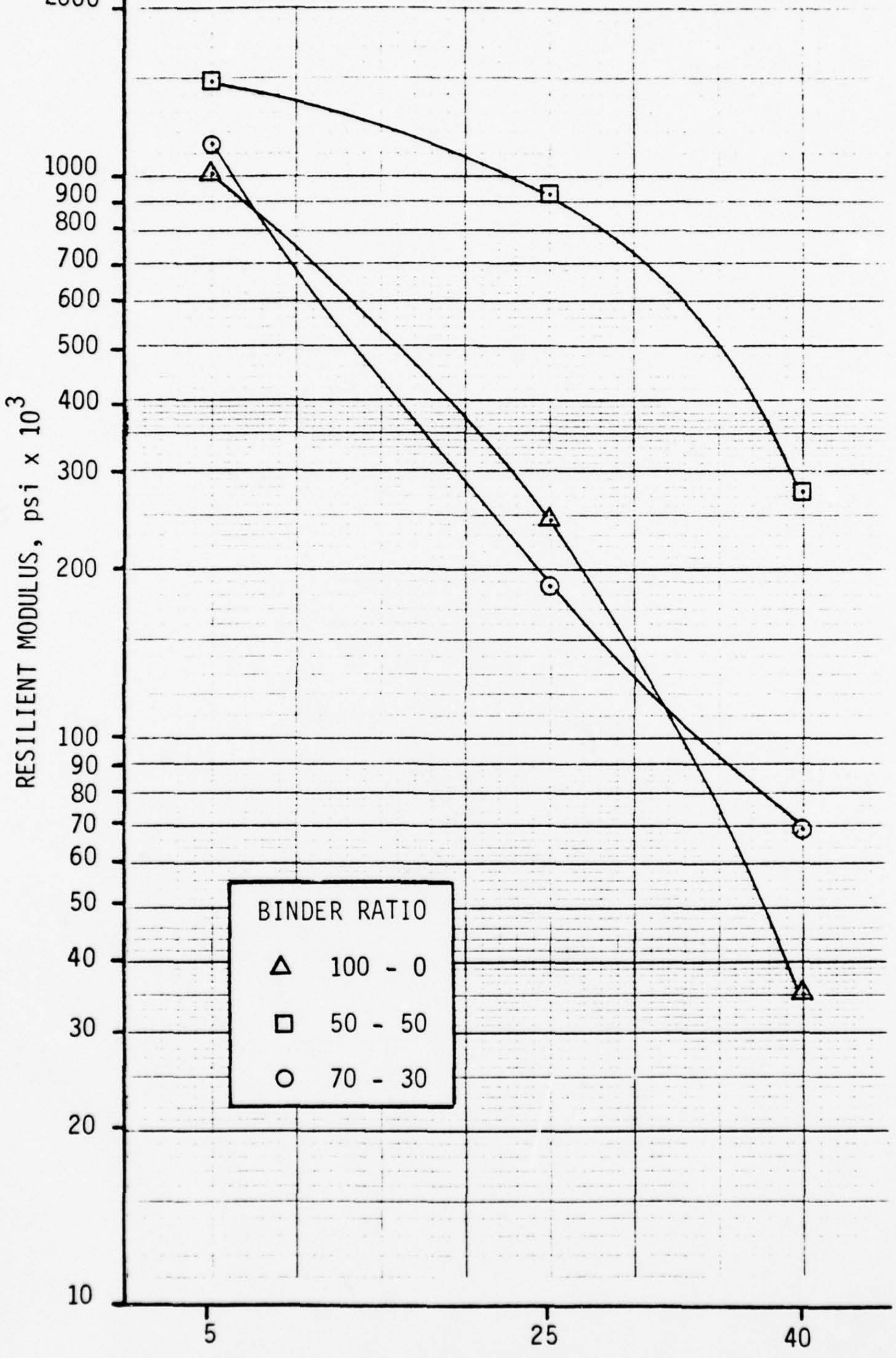


Figure 4.16 5.5% BINDER CONTENT, M_R VS TEMPERATURE: HVEEM SAMPLES

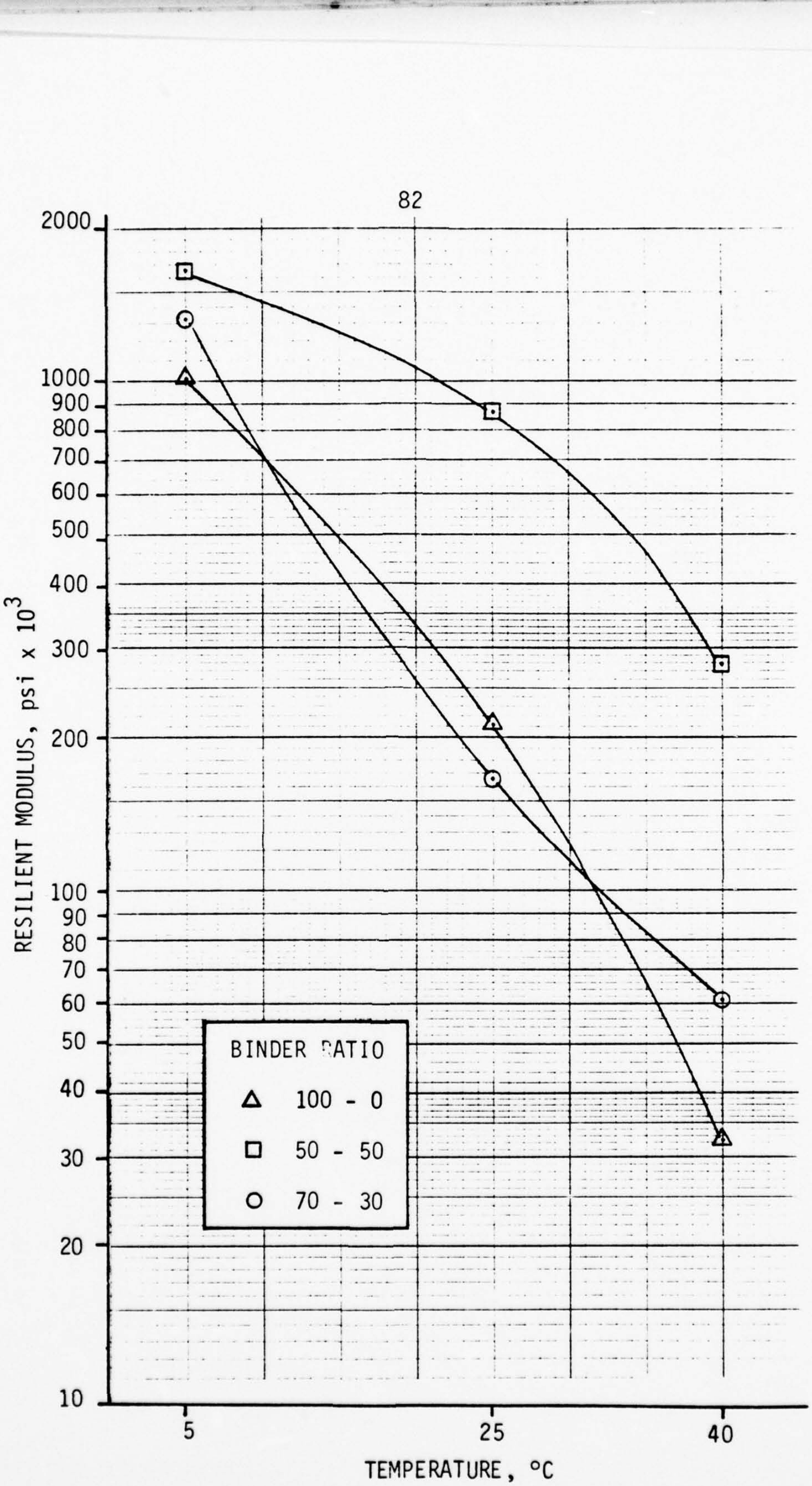


Figure 4.17 6.0% BINDER CONTENT, M_R VS TEMPERATURE: HVEEM SAMPLES

flat curve. This shows that the M_R value is not as great a function of temperature as the other two binder ratios. A totally flat curve would mean that temperature has no effect on the M_R value. The 100/0 and 70/30 curves show similar results at 25°C (77°F) but generally opposite results at 5°C (41°F) and 40°C (104°F). The 70/30 has higher values in the Hveem samples and lower in the Marshall. These results concur with those obtained by Pickett (37). As stated previously, many factors could have influenced these results.

The M_R testing has provided an additional dimension in the analysis of asphalt and SEA samples. It is very possible that a combination of M_R analysis and conventional mix design methods, or a modification of the existing methods, could be combined to determine the binder content for pavements with unusual materials.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Based upon laboratory procedures, experimental data and other information gained during this study, the following conclusions are made:

1. The Marshall and Hveem stabilities increase with the addition of sulphur.

2. The indirect tensile strength values of SEA samples increase with large amounts of sulphur (50/50) and decrease with small amounts (70/30) when compared to conventional (100/0) asphalt samples.

3. Generally, resilient modulus values of the Marshall samples increase from the 70/30, 100/0 to the 50/50 binder ratio samples.

4. Generally, resilient modulus values of the Hveem samples increase from the 100/0, 70/30 to the 50/50 binder ratio samples.

5. Changes in temperature have a lesser effect on the resilient modulus values for the 50/50 samples than the 100/0 or 70/30 samples.

6. The 100/0 and 70/30 samples exhibit similar values in all testing.

7. The recommended optimum binder content concurs with previous mix designs for the same aggregate and asphalt binder.

8. Exclusive use of an empirical design method developed for asphalt is questioned for unusual materials.

9. It is possible that a combination of the Hveem M_R value and the optimum binder content of a mix design be utilized to determine the final binder content used.

10. The laboratory results for this study and previous studies indicate the addition of sulphur to asphalt concrete pavements can produce a better, more economical pavement.

5.2 Recommendations

Based upon the conclusions stated above, the following recommendations for further study are made:

1. The concept of an "optimum binder content" be reviewed. This review should include a study to investigate the durability of a pavement should a low binder content be used in meeting the minimum criteria.

2. Researchers continue to investigate a mixture design procedure, or procedures, to adequately design a pavement when unusual materials, such as sulphur, are used. This design procedure should include a study to determine the "ideal" compaction temperature.

3. Additional research be conducted to investigate the resilient modulus testing procedure and its application to pavement design when unusual materials, such as sulphur, are involved.

4. A study using electron microscope photography be conducted on Marshall and Hveem SEA samples to determine any difference in the dispersion of the sulphur after compaction.

5. A resilient modulus study be conducted on cores from the test track to determine the relationship between the laboratory values and *in situ* values.

REFERENCES

1. Hornbostel, Caleb, Construction Materials, Types, Uses, and Applications, John Wiley and Sons, New York, NY, 1978.

2. "Energy Requirements for Roadway Pavements," MISC-75-3, a pamphlet published by the Asphalt Institute, April 1975.

3. Pickett, D.E., Saylak, D., Lytton, R.L., Conger, W.E., Newcomb, D. and Schapery, R.A., "Extension and Replacement of Asphalt Cement with Sulphur," Federal Highway Administration Report FHWA-RD-78-95, March 1978.

4. Sulphur, No. 109, November/December 1973.

5. "Sulphur: 1980's Shortage of Glut?", Chemical Engineering, September 27, 1976.

6. Terrel, Ronald L., Epps, J., and Al-Otaishan, Abdulaziz T., "Utilization of Sulphur in Pavements - Field Trip and Feasibility Report," University of Washington, Seattle, 1978.

7. Izatt, J.O., "Sulphur Extended Asphalt Field Trials - MH 153, Brazos County, Texas," A draft construction report, Texas Transportation Institute, Texas A&M University, September 1978.

8. Izatt, J.O., Gallaway, B.M., and Saylak, D., "Sand-Asphalt-Sulphur Pavement Field Trial, Highway U.S. 77, Kennedy County, Texas," a construction report, Federal Highway Administration Report FHWA-TS-78-204, April 1977.

9. Kennepohl, G.J.H., Logan, A. and Bean, D.C., "'Conventional' Paving Mixes with Sulphur-Asphalt Binders," a paper presented at the Annual Meeting of the Association of Asphalt Paving Technologists, February 1975.

10. Kennedy, T.W., Haas, R., Smith, P., Kennepohl, G.A. and Hignell, E.T., "An Engineering Evaluation of Sulphur-Asphalt Mixtures," a paper prepared for presentation at the 56th Annual Meeting of the Transportation Research Board, Austin Research Engineers, Incorporated, December 1976.

11. Lee, D., "Modification of Asphalt and Asphalt Paving Mixtures by Sulphur Additives," Engineering Research Institute, Iowa University, March 1971.

AD-A078 219 ARMY MILITARY PERSONNEL CENTER ALEXANDRIA VA F/G 7/2
MIX DESIGN AND RESILIENT MODULUS EVALUATION OF SULPHUR-EXTENDED--ETC(U)
NOV 79 P D SHARKEY

UNCLASSIFIED NL

2 OF 2
ADA
078219

END
DATE
FILMED
1 -80
DDC

12. McBee, W.C. and Sullivan, T.A., "Sulphur Utilization in Asphalt Paving Materials," New Uses in Sulphur-II, Advances in Chemistry Series, No. 165, American Chemistry Society, 1978.

13. Saylak, D., Gallaway, B.M. and Ahmad, H., "Beneficial Use of Sulphur in Sulphur-Asphalt Pavements," New Uses of Sulphur, Advances in Chemistry Series, No. 140, American Chemistry Society, 1975.

14. Saylak, D. and Gallaway, B., "Post Construction Evaluation of Sulphur-Asphalt Pavement Test Sections," Interim Report No. 3, FCIP Study No. 1-10-75-512, May 1977.

15. "Sulphur Utilization and Asphalt Conservation," a short course presented by the Texas Transportation Institute, Texas A&M University, June 1978.

16. Mahoney, J.P. and Terrel, R.L., "Sulphur-Extended Asphalt Binder Evaluation," a proposal submitted by the University of Washington to the Washington State Department of Transportation, May 1979.

17. ASTM Designation: C127-77, 1979 Annual Book of ASTM Standards, Part 14, American Society for Testing and Materials.

18. ASTM Designation: D 70, 1979 Annual Book of ASTM Standards, Part 14, American Society for Testing and Materials.

19. Evans, Michael L., "Preparation and Evaluation of Lignin-Extended Asphalt Binders and Mixtures," Master's Thesis, University of Washington, 1978.

20. Rimsritong, Sveng, "Wood Lignins Used as Extenders for Asphalt in Bituminous Pavements," Doctoral Dissertation, University of Washington, 1978.

21. Standard Specifications for Road and Bridge Construction, Washington State Highway Commission, Department of Highways, 1977.

22. ASTM Designation: D 1559, 1979 Annual Book of ASTM Standards, Part 15, American Society for Testing and Materials.

23. Rennie, W.J., "Sulphur Asphalts: The Pronk S/A Emulsion Binder System," Second Edition, No. 3, Sulphur Development Institute of Canada, 1978.

24. Pronk, F.E., Soderberg, A.F. and Frizzell, R.T., "Sulphur Modified Asphaltic Concrete," Annual Conference of the Canadian Technical Asphalt Association: Toronto, Ontario, 1975.

25. Bocca, P.L., Petrossi, U. and Piconi, V., "Heavy Hydrocarbons and Sulphur: Reactions and Reaction Products," La Chemica E L'Industria, 55, Maggio: 1973.

26. Tucker, J.R. and Schweyer, H.E., "Distribution and Reactions of Sulphur in Asphalt During Air Blowing and Sulphurizing Processes," Ind. Eng. Chem. Prod. Res. Dev., 4(1), p. 51, 1965.

27. Petrossi, U., Bocca, P.L. and Pacor, P., "Reactions and Technological Properties of Sulphur-Treated Asphalt," Ind. Eng. Chem. Prod. Res. Dev. 11 (2), p. 214, 1972.

28. Terrel, R.L., "Indirect Tensile Test Method for Resilient Modulus of Bituminous Mixtures," Proposed Draft of an ASTM Standard Method, Draft No. 6, November, 1978.

29. WDOT Test Method 704, Laboratory Manual, Washington State Highway Commission, Department of Highways, 1 July 1979.

30. WDOT Test Method 703, Laboratory Manual, Washington State Highway Commission, Department of Highways, 1 July 1979.

31. ASTM Designation: C 496, 1979 Annual Book of ASTM Standards, Part 14, American Society for Testing and Materials.

32. Yoder, E.J. and Witzak, M.W., Principles of Pavement Design, Second Edition, John Wiley and Sons, Inc., New York, NY, 1975.

33. WDOT Test Method 705, Laboratory Manual, Washington State Highway Commission, Department of Highways, 1 July 1979.

34. "Mix Design Methods for Asphalt Concrete and Other Hot-Mix Types," Asphalt Institute Manual Series, No. 2, The Asphalt Institute, July 1978.

35. Monismith, Carl L., "Asphalt Paving Mixtures - Properties, Design and Performance," course notes prepared for the Short Course in Asphalt Paving Technology, The Institute of Transportation and Traffic Engineering, University of California, 1961-62.

36. Phone conversation between Dr. Joseph P. Mahoney, Research Assistant Professor, University of Washington, and Mr. Jim Walter, Washington State Department of Transportation, 1978.

37. Pickett, Daniel E., "Extension and Replacement of Asphalt Cement with Sulphur," Master's Thesis, Texas A&M University, 1977.

38. Carniero, F.L.L.B. and Barcellus, A., "Union of Testing and Research Laboratory for Materials and Structures," No. 13, 1953.

39. Akazawa, Tseundo, "Uninion of Testing and Research Laboratory for Materials and Structures," No. 16, 1953.

40. Frocht, M.M., Photoelasticity, Vol. 2, John Wiley and Sons, New York, NY, 1948.

41. Timoshenko, S. and Goodier, J.N., Theory of Elasticity, 2nd Edition, McGraw-Hill, New York, NY, 1951.

42. Schmidt, R.J., "A Practical Method for Measuring the Resilient Modulus of Asphalt-Treated Mixes," Highway Research Record, No. 404, Highway Research Board, 1972.

APPENDIX A

PROPOSED DRAFT OF AN ASTM STANDARD METHOD "INDIRECT TENSILE TEST METHOD FOR RESILIENT MODULUS OF BITUMINOUS MIXTURES"

Draft No. 6
November, 1978
R.L. Terrel

INDIRECT TENSILE TEST METHOD

FOR

RESILIENT MODULUS OF BITUMINOUS MIXTURES

1. Scope

2. Applicable Documents

3. Summary of Method

4. Significance and Use

The values of the resilient modulus and resilient Poisson's ratio can be used for bituminous paving mixture design, as a supplement to standard values already used. The resilient properties can also be used in layered elastic analysis and thickness design of pavements. The test method may further be used in research investigations such as evaluation of materials performance with time (e.g. exposure tests) since the procedure is non-destructive.

5. Apparatus

6. Specimens

7. Procedures

8. Calculations

9. Report

Report the average resilient modulus at temperatures of 41, 77, and 104° F (5, 25, and 40° C) for each load and load frequency used in the test.

10. Precision

The precision of the method is being established.

Draft No. 6
November, 1978
R.L. Terrel

INDIRECT TENSILE TEST METHOD

FOR

RESILIENT MODULUS OF BITUMINOUS MIXTURES

ASTM DESIGNATION ____

1. Scope

1.1 This method covers procedures for preparing and testing laboratory or field recovered cores of bituminous mixtures to determine resilient modulus values using the repeated-load indirect tensile test. The procedure described covers a range of temperatures, loads, loading frequencies, and load durations. The minimum recommended test series consists of testing at 41, 77*, and 104° F (5, 25*, and 40° C) at a loading frequency of 0.33 to 1.0 Hz for each temperature. This recommended series will result in 9 test values for one specimen which can be used to evaluate the overall resilient behavior of the mixture.

2. Applicable Documents

2.1 ASTM Standards:

D 1559 Resistance to Plastic Flow of Bituminous Mixture Using Marshall Apparatus

---

*or ambient laboratory temperature as appropriate

D 1561 Preparation of Test Specimens of Bituminous Mixtures by Means of Kneading Compactor

D 3515 Hot-Mixed, Hot Laid Asphalt Paving Mixture

D 3496 Method for Preparation of Bituminous Mixture Cylindrical Specimens

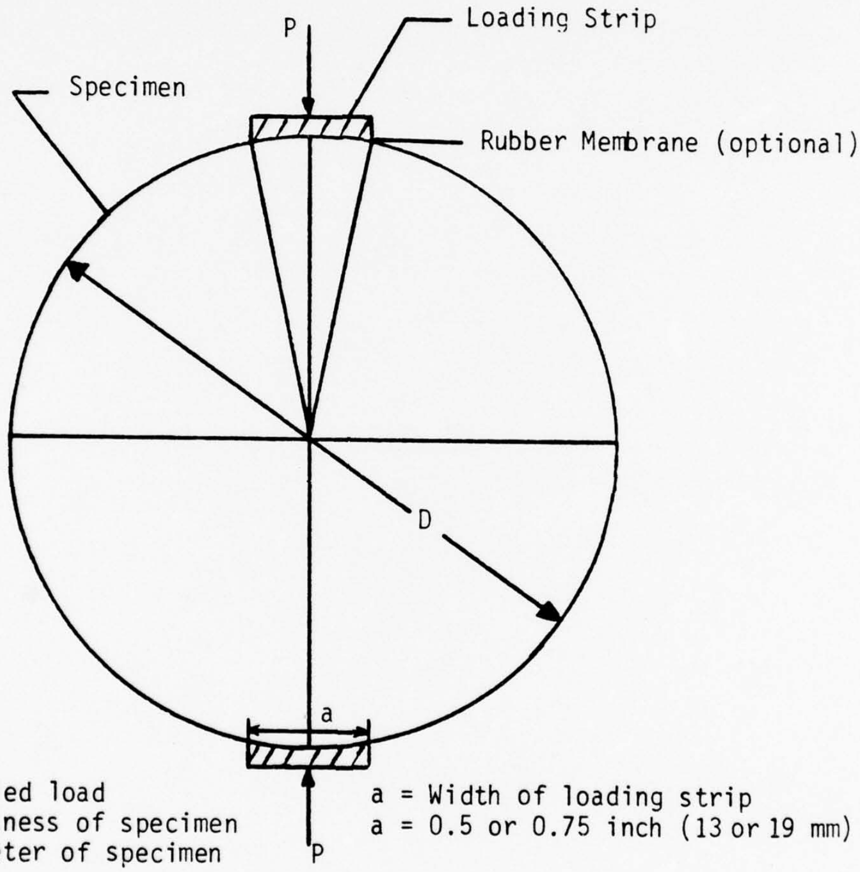
D 3387 Test for Compaction and Shear Properties of Bituminous Mixtures by Means of the U.S. Corps of Engineers Gyratory Testing Machine (GTM).

3. Summary of Method

3.1 The repeated-load indirect tensile test for resilient modulus is conducted by applying compressive loads with a haversine, square wave, or trapezoidal wave form. The loads act parallel to and along the vertical diametral plane of a cylindrical specimen of asphalt concrete (Fig. A-1) at a given temperature and loading frequency. The resulting recoverable horizontal deformation of the specimen is measured and used to calculate the resilient modulus of elasticity with an assumed value of Poisson's ratio or with a calculated value using the measured recoverable vertical deformation.

4. Significance and Use

4.1 The values of the resilient modulus and resilient Poisson's ratio can be used for bituminous paving mixture design, as a supplement to standard values already used. The resilient properties can also be used in layered elastic analysis and thickness design of pavements.



P = Applied load
t = Thickness of specimen
D = Diameter of specimen

a = Width of loading strip
a = 0.5 or 0.75 inch (13 or 19 mm)

Figure A-1. Indirect Tensile Test

The test method may further be used in research investigations such as evaluation of materials performance with time (e.g. exposure tests) since the procedure is non-destructive.

5. Apparatus

5.1 Testing machine - The testing machine should have the capability of applying a load pulse over a range of frequencies, load durations, and load levels.

> Note 1 - An electro-hydraulic testing machine with a function generator capable of producing the prescribed wave form has been shown to be suitable for use in repeated-load indirect tensile testing; other commercially available or laboratory constructed testing machines such as those using pneumatic repeated loading can also be used. However, these machines may not have the load capability to handle larger specimens at the colder testing temperatures.

5.2 Temperature control system - The temperature control system should be capable of control over a temperature range. The temperature chamber should be large enough to hold an adequate number of specimens for a period of 24 hours prior to testing.

5.3 Measurement System - The measurement system should include a recorder or other measuring device for the horizontal and vertical deformations. If Poisson's ratio is to be assumed, then only horizontal deformations must be recorded. Loads should be measured and recorded or accurately calibrated prior to testing. The system should

be capable of measuring deformations in the range of 0.00001 inches (0.00025mm) of deformation. An alternate system could give deformation readout directly by suitable calibration of the loading and measurement components.

5.3.1 Recorder - The recorders should be independent of frequency for tests conducted up to 1.0 Hz.

5.3.2 Deformation Measurement - The values of vertical and horizontal deformation are measured by LVDT's or other suitable devices. The horizontal LVDT's should be at mid-height opposite each other on the specimens horizontal diameter. The sensitivity and type of measurement device should be selected to provide the deformation readout required in Section 4.3.

> Note 2 - The Trans-TEX Model 350-000 LVDT and Statham UC-3 transducers have been found satisfactory for this purpose.
>
> Note 3 - The gages should be wired to preclude the effects of eccentric loading so as to give the algebraic sum of the movement of each side of the specimen. Alternatively, each gage can be read independently and the results summed separately.

5.3.3 Load Measurement - Loads are measured with an electronic load cell capable of satisfying the specified requirements for load measurements in Section 5.3.

5.4 Loading Strip - A steel or aluminum curved-loading strip with radius equal to that of the test specimen is required to transfer the load from the testing machine to the specimen. The load strip shall be 0.5 or 0.75 inches (13 or 19 mm) wide for 4.0 or 6.0 inch (102 or 150 mm) diameter specimens, respectively; edges should be rounded in order to not cut the sample during testing. For specimens with rough textures, a thin hard rubber membrane attached to the loading strip has been found effective in reducing impact loading effects if vertical deformations are not monitored.

6. Specimens

6.1 Laboratory Molded Specimens - Prepare the laboratory molded specimens according to acceptable procedures such as ASTM Method D 1561. The specimens should have a height of at least 2 inches (50 mm) and a minimum diameter of 4 inches (102 mm), but not less than four times the maximum nominal size of the aggregate particles.

6.2 Pavement Cores - Core samples from an inservice pavement should have a minimum height of 1.5 to 2 inches (38 to 50 mm) and diameters of at least 4 inches (102 mm) but not less than four times the maximum nominal size of the aggregate particles. Cores should have relatively smooth parallel surfaces.

> Note 4 - Laboratory molded specimens and pavement cores with diameters of 6 inches (150 mm) and heights of 3 inches (75 mm) or more have been used.

7. Procedures

7.1 Place test specimens in a controlled temperature cabinet and bring them to the specified test temperature. Unless temperature is monitored, and the actual temperature known, the specimens should remain in the cabinet at the specified test temperature for at least 24 hours prior to testing.

Note 5 - A dummy specimen with a thermocouple in the center can be used to determine when the desired test temperature is reached.

7.2 Place specimen into loading apparatus and position the steel or aluminum loading strips. Adjust and balance electronic measuring system as necessary.

7.3 Apply a preconditioning loading consisting of a repeated haversine, or other suitable waveform, loading to the specimen without impact for a minimum period sufficient to obtain uniform deformation readout. Depending upon the loading frequency, a minimum of 50 to 200 load repetitions is generally sufficient; however, the minimum for a given situation must be determined so that the resilient deformations are stable. A complete test will usually include measurements at three temperatures, e.g., 41 ± 2, 77 ± 2, and 104 ± 2°F (5, 25, and 40°C), at one or more loading frequencies, e.g., 0.33, 0.5, and 1.0 Hz, for each temperature. Recommended load range is from 10 to 50 per cent of the tensile strength. Tensile strength can be determined from a destructive test on a specimen and the equation of Section 8.3.

Note 6 - Load duration is the more important variable and it is recommended that the duration be held to some minimum which can be recorded. The recommended range for load duration is 0.04 to 0.4 sec., with 0.1 sec. being representative of transient pavement loading. Recommended frequencies are 0.33 to 1.0 Hz. In lieu of tensile strength data, load ranges from 25 to 200 lbs.

7.4 Monitor the vertical and horizontal deformations during the test.

Note 7 - A typical load pulse-deformation trace is shown in Fig. A-2, along with notations indicating the load-time terminology.

7.5 Each test should be completed within two minutes from the time specimens are removed from the temperature control cabinet.

Note 8 - The two minute testing time limit is waived if loading is conducted within a temperature control cabinet meeting requirements in Section 5.2.

7.6 Each specimen should be tested more than once by rotating the specimen and loading through another diametral plane. Three laboratory fabricated specimens or three cores are recommended for a given test series with variables of temperature, load duration, and load. In order to reduce permanent damage to the specimen, testing should begin at the lowest temperature, shortest load duration, and smallest load. Subsequent testing on the same specimen should be for conditions producing progressively lower moduli. Bring specimens to specified temperature before each test.

Note 9 - If excessive total deformation, i.e., greater than 0/001 inch (0.0254 mm), occurs during a test, reduce the applied load, the test temperature, or both.

8. Calculations

8.1 Measure the average recoverable horizontal and vertical deformations over at least three loading cycles (see Fig. A-2) after the repeated resilient deformation has become stable.

8.2 Calculate the resilient modulus of elasticity E_R and Poisson's ratio ν using the following equations:

$$E_R = \frac{P(\nu + 0.27)}{t\Delta_x}, \text{ psi}$$

$$\nu = 3.59 \frac{\Delta_x}{\Delta_y} - 0.27$$

where

P = repeated load, lb.

ν = Poisson's ratio

t = thickness of specimen, in.

Δ_x = recoverable horizontal deformation, in.

Δ_y = recoverable vertical deformation, in.

Note 10 - Poisson's ratio can be calculated using the above equation for 4-inch and 6-inch diameter specimens with 0.5 inch or 0.75 inch wide loading strips, respectively, or the value can be assumed in which case vertical deformations are not required. A value of

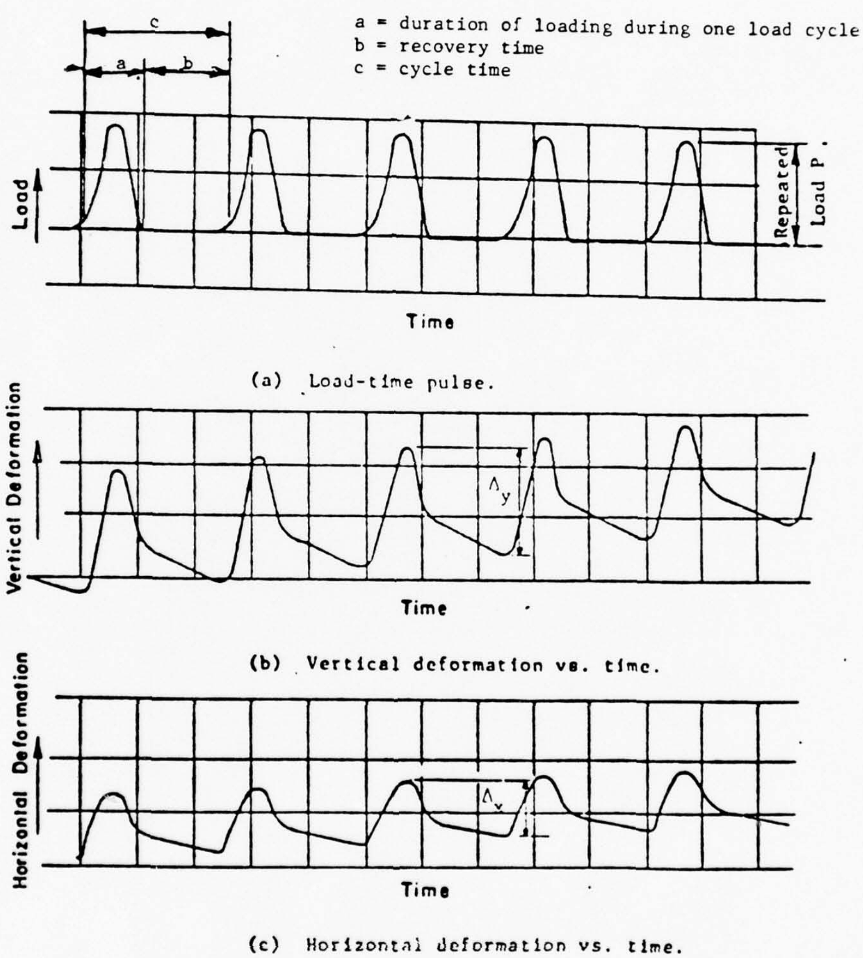


Figure A-2. Typical Load and Deformation Versus Time Relationships for Repeated-Load Indirect Tensile Test

0.35 for Poisson's ratio has been found to be reasonable for asphalt mixtures at 77°F (25°C).

8.3 The tensile strength S_T can be calculated using the following equation:

$$S_T = \frac{2P_{ult}}{\pi td}$$

where

P_{ult} = the ultimate applied load required to fail specimen, lb.

t = thickness of specimen, in.

D = diameter of specimen, in.

9. Report

9.1 Report the average resilient modulus at temperatures of 41, 77, and 104°F (5, 25, and 40°C) for each load and load frequency used in the test.

10. Precision

10.1 The precision of the method is being established.

APPENDIX B

RESILIENT MODULUS DATA

.3 POISSON'S RATIO (ASSUMED)

Table B-1. RESILIENT MODULUS VALUES (psi x 10^3)
MARSHALL MIX DESIGN SAMPLES (A)
ASPHALT/SULPHUR RATIO 100/0
.3 POISSON'S RATIO

DAY	BINDER CONTENT (% BY WEIGHT) 4.5	5.0	5.5	6.0	6.5
1	430.5	289.8	382.6	329.3	304.0
2	483.5	304.8	349.6	302.1	279.5
3	420.9	309.1	433.1	362.2	308.9
4	476.8	332.9	427.1	345.0	319.7
5	470.8	321.7	421.4	380.1	334.4
6	338.1	246.2	314.5	279.1	261.6
$7_{5°C}$	954.1	845.5	851.7	928.0	976.0
$7_{25°C}$	356.0	220.0	298.9	253.1	237.5
$7_{40°C}$	49.9	39.0	49.1	33.9	30.2

Table B-2. RESILIENT MODULUS VALUES (psi x 10^3)
MARSHALL MIX DESIGN SAMPLES (B)
ASPHALT/SULPHUR RATIO 50/50
.3 POISSON'S RATIO

DAY	BINDER CONTENT (% BY WEIGHT) 4.5 (6.1)	5.0 (6.7)	5.5 (7.4)	6.0 (8.1)	6.5 (8.8)
1	967.8	664.5	493.1	486.2	359.3
2	897.3	774.7	593.8	548.4	403.1
3	564.2	398.8	324.7	300.5	227.2
4	603.0	425.3	365.2	322.0	284.6
5	647.6	469.0	406.9	366.3	303.8
6	657.3	530.5	437.0	385.1	319.6
$7_{5°C}$	1178.5	987.8	923.2	921.3	811.3
$7_{25°C}$	809.6	692.0	701.1	729.0	742.4
$7_{40°C}$	606.2	623.0	526.2	466.2	318.4

Table B-3. RESILIENT MODULUS VALUES (psi x 10^3)
MARSHALL MIX DESIGN SAMPLES (C)
ASPHALT/SULPHUR RATIO 70/30
.3 POISSON'S RATIO

DAY	BINDER CONTENT (% BY WEIGHT) 4.5 (5.3)	5.0 (5.9)	5.5 (6.5)	6.0 (7.1)	6.5 (7.7)
1	184.7	139.6	95.2	84.6	66.8
2	175.8	145.2	109.5	88.1	72.5
3	203.2	149.0	115.6	100.5	85.3
4	184.7	149.9	104.1	86.7	83.2
5	208.9	172.6	123.1	115.3	102.5
6	293.8	217.4	170.2	146.2	134.8
$7_{5°C}$	780.6	656.8	572.1	591.8	559.3
$7_{25°C}$	264.6	222.0	172.5	160.3	168.9
$7_{40°C}$	54.7	45.6	35.1	33.5	48.1

Table B-4. RESILIENT MODULUS VALUES (psi x 10^3)
HVEEM MIX DESIGN SAMPLES (D)
ASPHALT/SULPHUR RATIO 100/0
.3 POISSON'S RATIO

DAY	BINDER CONTENT (% BY WEIGHT) 4.0	4.5	5.0	5.5	6.0
1	98.8	110.7	145.9	162.5	145.2
2	94.5	123.4	158.9	179.8	178.7
3	113.1	135.4	168.7	194.8	176.7
4	106.1	140.9	162.6	199.4	186.6
5	100.8	124.0	159.1	191.1	171.5
6	98.8	121.5	146.4	185.9	168.3
$7_{5°C}$	1020.8	1030.5	896.5	1006.3	1002.4
$7_{25°C}$	124.4	151.6	185.4	245.6	211.8
$7_{40°C}$	30.0	24.6	31.8	35.1	32.6

Table B-5. RESILIENT MODULUS VALUES (psi x 10^3)
HVEEM MIX DESIGN SAMPLES (E)
ASPHALT/SULPHUR RATIO 50/50
.3 POISSON'S RATIO

	BINDER CONTENT (% BY WEIGHT) 4.0 (5.4)	4.5 (6.1)	5.0 (6.7)	5.5 (7.4)	6.0 (8.1)
DAY 1	145.3	261.1	488.1	537.0	583.5
2	220.6	392.3	743.2	898.6	862.9
3	247.7	430.5	639.4	777.5	709.1
4	267.7	465.9	710.5	733.2	694.7
5	267.7	534.6	770.1	850.3	843.4
6	398.4	644.2	878.4	893.6	807.4
$7_{5°C}$	1231.8	1538.7	1439.7	1496.3	1666.9
$7_{25°C}$	376.3	618.1	837.5	927.1	866.0
$7_{40°C}$	198.9	249.6	280.3	275.6	279.7

Table B-6. RESILIENT MODULUS VALUES (psi x 10^3)
HVEEM MIX DEISGN SAMPLES (F)
ASPHALT SULPHUR RATIO 70/30
.3 POISSON'S RATIO

DAY	BINDER CONTENT (% BY WEIGHT) 4.0 (4.7)	4.5 (5.3)	5.0 (5.9)	5.5 (6.5)	6.0 (7.1)
1	80.0	92.4	106.6	119.6	110.9
2	74.2	89.7	98.9	122.2	124.9
3	74.2	85.1	112.7	125.5	115.8
4	68.3	99.5	124.9	164.9	152.6
5	70.8	91.7	119.7	136.4	115.0
6	72.3	97.7	136.4	160.3	143.8
$7_{5°C}$	1008.2	1251.1	1151.4	1147.5	1320.6
$7_{25°C}$	73.5	110.9	157.4	187.8	166.0
$7_{40°C}$	25.5	44.1	62.9	69.2	60.6

APPENDIX C

RESILIENT MODULUS DATA

CALCULATED POISSON'S RATIO

Table C-1. RESILIENT MODULUS VALUES (psi x 10^3)
MARSHALL MIX DESIGN SAMPLES (A)
ASPHALT/SULPHUR RATIO 100/0
CALCULATED POISSON'S RATIO

DAY	BINDER CONTENT (% BY WEIGHT) 4.5	5.0	5.5	6.0	6.5
1	444.2	293.8	393.4	330.9	309.8
2	499.8	310.6	356.9	305.3	282.0
3	431.5	313.1	443.1	369.7	314.3
4	490.1	336.3	435.5	349.1	323.3
5	485.0	327.8	432.6	389.5	340.3
6	371.9	246.3	317.5	280.5	261.2
$7_{5°C}$	988.5	877.7	882.9	959.4	1012.3
$7_{25°C}$	361.3	216.9	300.5	252.5	236.1
$7_{40°C}$	42.4	32.0	41.4	26.0	22.5

Table C-2. RESILIENT MODULUS VALUES (psi x 10^3)
MARSHALL MIX DESIGN SAMPLES (B)
ASPHALT/SULPHUR RATIO 50/50
CALCULATED POISSON'S RATIO

	BINDER CONTENT (% BY WEIGHT)				
DAY	4.5 (6.1)	5.0 (6.7)	5.5 (7.4)	6.0 (8.1)	6.5 (8.8)
1	1006.9	686.1	505.9	496.4	361.5
2	930.4	802.9	611.5	561.3	408.3
3	579.8	403.9	327.5	297.0	212.1
4	602.9	417.8	358.6	307.5	332.6
5	664.5	475.2	409.9	366.7	303.2
6	722.0	542.2	440.0	381.7	319.6
$7_{5°C}$	1205.4	1017.6	952.0	933.4	836.5
$7_{25°C}$	837.2	711.6	720.8	752.3	760.9
$7_{40°C}$	784.6	641.3	539.2	472.2	315.0

Table C-3. RESILIENT MODULUS VALUES (psi x 10^3)
MARSHALL MIX DESIGN SAMPLES (C)
ASPHALT/SULPHUR RATIO 70/30
CALCULATED POISSON'S RATIO

DAY	BINDER CONTENT (% BY WEIGHT) 4.5 (5.3)	5.0 (5.9)	5.5 (6.5)	6.0 (7.1)	6.5 (7.7)
1	180.5	133.4	87.0	76.4	57.8
2	159.1	128.3	89.1	68.6	52.0
3	186.1	125.5	95.8	77.1	64.1
4	179.5	143.7	96.0	78.2	75.7
5	200.4	165.3	112.8	102.1	91.4
6	288.4	208.1	157.7	137.5	122.0
$7_{5°C}$	799.9	667.1	571.3	397.4	561.6
$7_{25°C}$	263.7	217.4	166.7	149.5	159.2
$7_{40°C}$	42.6	32.7	22.3	21.9	38.6

Table C-4. RESILIENT MODULUS VALUES (psi x 10^3)
HVEEM MIX DESIGN SAMPLES (D)
ASPHALT/SULPHUR RATIO 100/0
CALCULATED POISSON'S RATIO

		BINDER CONTENT (% BY WEIGHT)				
		4.0	4.5	5.0	5.5	6.0
DAY	1	90.4	100.8	136.0	150.2	136.9
	2	86.1	114.5	150.9	168.6	171.0
	3	104.8	119.8	155.1	187.3	167.8
	4	100.7	136.9	158.9	196.5	181.6
	5	91.2	117.4	146.5	175.7	157.6
	6	87.0	106.9	133.4	174.2	156.2
	$7_{5°C}$	1054.7	1067.6	910.5	1025.0	1024.0
	$7_{25°C}$	116.6	143.4	178.7	241.2	191.6
	$7_{40°C}$	30.0	24.6	31.8	35.1	32.6

Table C-5. RESILIENT MODULUS VALUES (psi x 10^3)
HVEEM MIX DESIGN SAMPLES (E)
ASPHALT/SULPHUR RATIO 50/50
CALCULATED POISSON'S RATIO

DAY	BINDER CONTENT (% BY WEIGHT) 4.0 (5.4)	4.5 (6.1)	5.0 (6.7)	5.5 (7.4)	6.0 (8.1)
1	137.6	259.9	493.5	538.7	586.4
2	210.4	394.2	756.7	919.8	873.5
3	247.4	439.7	658.7	802.9	729.8
4	260.3	470.9	723.7	749.4	708.9
5	262.8	544.8	792.0	874.1	886.3
6	402.7	662.0	939.2	925.7	829.5
$7_{5°C}$	1275.8	1598.9	1492.6	1548.3	1716.0
$7_{25°C}$	374.8	624.9	852.2	922.1	866.0
$7_{40°C}$	192.2	246.7	271.5	265.5	272.4

Table C-6. RESILIENT MODULUS VALUES (psi x 10^3)
HVEEM MIX DESIGN SAMPLES (F)
ASPHALT/SULPHUR RATIO 70/30
CALCULATED POISSON'S RATIO

DAY	BINDER CONTENT (% BY WEIGHT) 4.0 (4.7)	4.5 (5.3)	5.0 (5.9)	5.5 (6.5)	6.0 (7.1)
1	68.4	79.8	95.1	106.9	99.2
2	67.6	81.9	89.3	113.0	115.4
3	63.8	78.2	105.2	115.5	105.7
4	51.9	87.8	111.8	119.7	126.2
5	58.5	78.0	108.8	123.6	117.3
6	59.4	82.7	122.9	144.8	127.9
$7_{5°C}$	1039.3	1296.0	1188.8	1184.5	1368.4
$7_{25°C}$	60.5	95.7	143.0	174.6	149.4
$7_{40°C}$	14.1	44.1	62.9	61.2	48.8

APPENDIX D

CALCULATED POISSON'S RATIO DATA

Table D-1. POISSON'S RATIO VALUES
MARSHALL MIX DESIGN SAMPLES (A)
ASPHALT/SULPHUR RATIO 100/0

DAY	BINDER CONTENT (% BY WEIGHT) 4.5	5.0	5.5	6.0	6.5
1	.318	.307	.317	.311	.310
2	.319	.311	.312	.306	.305
3	.315	.307	.314	.312	.310
4	.316	.306	.311	.307	.306
5	.318	.311	.315	.313	.310
6	.311	.300	.305	.303	.299
$7_{5°C}$	.320	.322	.321	.319	.321
$7_{25°C}$	.309	.292	.303	.299	.296
$7_{40°C}$	.213	.197	.209	.165	.144

Table D-2. POISSON'S RATIO VALUES
MARSHALL MIX DESIGN SAMPLES (B)
ASPHALT/SULPHUR RATIO 50/50

DAY	BINDER CONTENT (% BY WEIGHT) 4.5 (6.1)	5.0 (6.7)	5.5 (7.4)	6.0 (8.1)	6.5 (8.8)
1	.322	.317	.314	.305	.299
2	.320	.320	.316	.308	.303
3	.315	.305	.304	.286	.256
4	.299	.286	.289	.263	.259
5	.315	.308	.304	.295	.297
6	.315	.311	.303	.290	.298
$7_{5°C}$	.320	.316	.317	.316	.318
$7_{25°C}$	.316	.315	.315	.317	.312
$7_{40°C}$	.319	.314	.313	.300	.283

Table D-3. POISSON'S RATIO VALUES
MARSHALL MIX DESIGN SAMPLES (C)
ASPHALT/SULPHUR RATIO 70/30

		BINDER CONTENT (% BY WEIGHT)				
		4.5 (5.3)	5.0 (5.9)	5.5 (6.5)	6.0 (7.1)	6.5 (7.7)
DAY	1	.286	.274	.251	.241	.222
	2	.245	.234	.189	.172	.137
	3	.249	.210	.201	.166	.157
	4	.283	.275	.255	.235	.245
	5	.275	.275	.252	.233	.235
	6	.288	.275	.258	.253	.245
	$7_{5°C}$	.312	.308	.298	.308	.301
	$7_{25°C}$	.298	.288	.281	.262	.267
	$7_{40°C}$	.167	.134	.091	.096	.154

Table D-4. POISSON'S RATIO VALUES
HVEEM MIX DESIGN SAMPLES (D)
ASPHALT/SULPHUR RATIO 100/0

DAY	BINDER CONTENT (% BY WEIGHT) 4.0	4.5	5.0	5.5	6.0
1	.251	.248	.260	.261	.267
2	.249	.259	.270	.264	.275
3	.256	.233	.253	.273	.271
4	.270	.283	.286	.292	.285
5	.245	.270	.253	.253	.254
6	.229	.229	.248	.264	.258
$7_{5°C}$	.319	.321	.308	.309	.312
$7_{25°C}$	.264	.261	.270	.289	.272
$7_{40°C}$	.116	.048	.125	.140	.108

Table D-5. POISSON'S RATIO VALUES
HVEEM MIX DESIGN SAMPLES (E)
ASPHALT/SULPHUR RATIO 50/50

DAY	BINDER CONTENT (% BY WEIGHT) 4.0 (5.4)	4.5 (6.1)	5.0 (6.7)	5.5 (7.4)	6.0 (8.1)
1	.261	.296	.306	.302	.300
2	.269	.300	.310	.313	.316
3	.294	.310	.316	.318	.314
4	.282	.304	.310	.312	.309
5	.281	.309	.315	.315	.307
6	.304	.315	.319	.320	.314
$7_{5°C}$	.320	.322	.321	.320	.324
$7_{25°C}$	.296	.306	.310	.297	.304
$7_{40°C}$	.280	.293	.281	.279	.282

Table D-6. POISSON'S RATIO VALUES
HVEEM MIX DESIGN SAMPLES (F)
ASPHALT/SULPHUR RATIO 70/30

DAY	BINDER CONTENT (% BY WEIGHT) 4.0 (4.7)	4.5 (5.3)	5.0 (5.9)	5.5 (6.5)	6.0 (7.1)
1	.213	.215	.237	.238	.237
2	.246	.249	.244	.257	.255
3	.215	.252	.262	.252	.249
4	.159	.226	.237	.232	.265
5	.200	.214	.245	.246	.236
6	.195	.210	.243	.241	.237
$7_{5°C}$	.317	.321	.318	.318	.321
$7_{25°C}$	.195	.221	.246	.259	.243
$7_{40°C}$	.042	.145	.185	.204	.188

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER

2. GOVT ACCESSION NO.

3. RECIPIENT'S CATALOG NUMBER

4. TITLE (and Subtitle)
MIX DESIGN AND RESILIENT MODULUS EVALUATION OF SULPHUR-EXTENDED ASPHALT PAVEMENTS

5. TYPE OF REPORT & PERIOD COVERED
Final Report
5 November 1979

6. PERFORMING ORG. REPORT NUMBER

7. AUTHOR(s)
PAUL D. SHARKEY

8. CONTRACT OR GRANT NUMBER(s)

9. PERFORMING ORGANIZATION NAME AND ADDRESS
Student, HQDA, MILPERCEN (DAPC-OPP-E),
200 Stovall Street
Alexandria, VA 22332

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS

11. CONTROLLING OFFICE NAME AND ADDRESS
HQDA, MILPERCEN, ATTN: DAPC-OPP-E
200 Stovall Street
Alexandria, VA 22332

12. REPORT DATE
5 November 1979

13. NUMBER OF PAGES
125

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)

15. SECURITY CLASS. (of this report)

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
UNCLASSIFIED

16. DISTRIBUTION STATEMENT (of this Report)
Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES
Thesis, University of Washington, Seattle, Washington

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)
Sulphur-Extended Asphalt, Asphalt Mix Design, Resilient Modulus, Mix Design of Sulphur-Extended Asphalt

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)
The increased price and questionable availability of asphalt has led to the investigation of alternate binders. One such binder is sulphur. This study has investigated the mix design properties of both the Marshall and Hveem mix designs as well as the resilient modulus values. Various sulphur/asphalt binder ratios were compared to the conventional aphalt pavement. The study has shown that the addition of sulphur can provide a better pavement.

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

79 22 3 145

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)